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Uncertainty Estimation in Antenna Measurements

by

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&

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Abstract: This tutorial focuses on the fundamentals, importance and the method of estimating uncertainty in antenna radiation pattern measurements. The tutorial would begin with a brief review of antenna measurement ranges and basics of gain measurement. Outlining the need for reporting a statement of uncertainty in any gain measurement, the tutorial will then look at the different factors that contribute to uncertainty in pattern and gain measurement in a free-space range. Data from recent measurement efforts will be employed for illustration. Special effort will be made to show some examples of the antenna measurements including omni-directional antennas, directional antennas, circularly polarized antennas, reconfigurable antennas, tunable antennas, null steering antennas, and beam steering antennas, etc.

Keywords: Gain Measurement, Horn, Measurement Errors, Multipath interference, Pattern measurement, Two Antenna Method, Uncertainty Analysis

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Krishnasamy T. Selvan obtained his BE (Hons), MS and PhD degrees respectively from Madurai Kamaraj University (1987), Birla Institute of Technology and Science (1996) and Jadavpur University (2002). He also obtained a PGCHE in Higher Education from University of Nottingham in 2007.

Selvan has been a Professor in the Department of Electronics and Communication Engineering, SSN College of Engineering, India, since June 2012. From early 2005 to mid-2012, he was with the Department of Electrical and Electronic Engineering, University of Nottingham Malaysia Campus. He also held the positions of the Assistant Director of Teaching and Learning for the Faculty of Engineering and the Deputy Director of Studies of the Department of Electrical and Electronic Engineering.

From early 1988 to early 2005, Selvan was with SAMEER – Centre for Electromagnetics, Chennai, India. During 1994–1997, he was the Principal Investigator of a collaborative research programme that SAMEER had with the National Institute of Standards and Technology, USA. Later he was the Project Manager/Leader of some successfully completed antenna development projects.

Selvan's professional interests include electromagnetics, antenna metrology, horn antennas, printed antennas, and electromagnetic education. In these areas, he has authored or coauthored a number of journal and conference papers. Selvan was on the editorial boards of the International Journal of RF and Microwave Computer-Aided Engineering and the International Journal on Antennas and Propagation. He has been a reviewer for major journals including the IEEE Transactions on Antennas and Propagation. He was technical programme committee co-chair for the IEEE Applied

Electromagnetics Conference held in Kolkata in December 2011, and Student Paper Contest co-chair for IEEE AEMC 2013 to be held in Bhubaneswar. He was Publications Chair for the IEEE MTT-S International Microwave and RF Symposium (IMaRC) held in Bangalore in December 2014. He co-organized sessions on EM/microwave education during IMaRC 2014 and International Symposium on Antennas and Propagation, Kochi, 2014.

Selvan founded the Madras Chapter of the IEEE Antennas and Propagation Society (AP-S) in 2013. He is a member of the Education Committee of the IEEE Antennas and Propagation Society. He is an IEEE AP-S Region 10 Distinguished Speaker for 2015-16.

Selvan is a senior member of the IEEE, a Fellow of the Higher Education Academy (UK), and a Life Member of the Society of EMC Engineers (India).

Satish Kumar Sharma received his B. Tech. degree from Kamla Nehru Institute of Technology and Ph. D. degree from the Indian Institute of Technology (IIT), Banaras Hindu University (BHU) in 1991 and 1997, respectively, both in Electronics Engineering. From March 1999 to April 2001, he was a Postdoctoral Fellow in the Department of Electrical and Computer Engineering, University of Manitoba, Manitoba, Canada. He was a Senior Antenna Engineer with InfoMagnetics Technologies Corporation in Winnipeg, Manitoba, Canada, from May 2001 to August 2006. Simultaneously, he was also a Research Associate at the University of Manitoba from June 2001 to August 2006.

In August 2006, he joined San Diego State University (SDSU), San Diego as an Assistant Professor in the Department of Electrical and Computer Engineering. Here, he has developed an Antenna Laboratory, teaches courses in Applied Electromagnetics, and advises several MS and Ph D graduate students. Currently, he is a Professor and Director of the Antenna and Microwave Laboratory (AML). He is author/coauthor of more than 150 research papers published in the referenced international journals and conferences. Recently, he co-edited three volumes of "*Handbook of Reflector Antennas and Feed Systems, Volume 1: Theory and Design of Reflectors, Volume II: Feed Systems, and Volume III: Applications of Reflectors*" published by Artech House, USA, which also has several coauthored chapter contributions by him. He holds 1 US and 1 Canadian patents. His main research interests are in the microstrip antennas, ultra-wide, wideband, multiband and broadband antennas, reconfigurable, tunable and frequency agile antennas, feeds for reflector antennas, waveguide horns and polarizers, electrically small antennas, MIMO antennas, phased array antennas, wire antennas, active antennas and microwave passive components.

Dr. Sharma received the National Science Foundation's prestigious faculty early development (CAREER) award in 2009 and the Young Scientist Award of URSI Commission B, Field and Waves, during the URSI Triennial International Symposium on Electromagnetic Theory, Pisa, Italy, in 2004. He was recognized as the Outstanding Associate Editor (AE) for the *IEEE Transaction on Antennas and Propagation* (IEEE TAP) journal in July 2014. Most recently, his co-authored IEEE Trans on Antennas and Propagation paper received prestigious 2015 IEEE Antenna and Propagation Harold A. Wheeler Applications Prize Award. He is serving as the AE for the IEEE TAP since 2010. He was Chair/Co-Chair of the several Student Paper Contests in different conferences and symposia and served on the sub-committee of the Education Committee for the IEEE Antennas and Propagation Society for the organization of the Student Paper Contests. He is a Senior Member of IEEE and full member of the USNC/URSI, Commission B, Fields and Waves.

Uncertainty Estimation in Antenna Measurements

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Broad contents

- Uncertainty estimation in antenna calibration

  by KT Selvan

- Challenges in pattern measurements

  by Satish Sharma

Uncertainty Estimation in Antenna Gain Measurements

K T Selvan

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Objectives

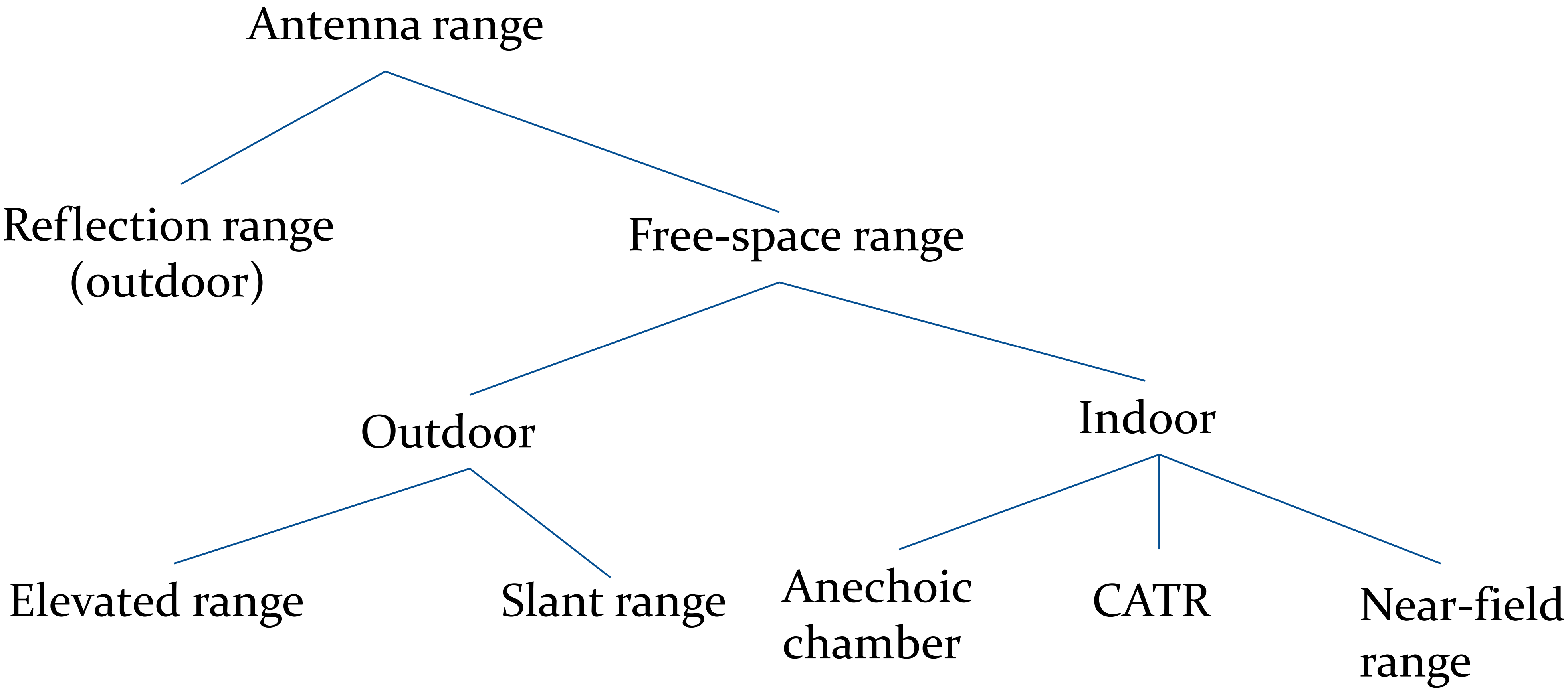
- To discuss the challenges in antenna measurements
- To ignite interest in the important and interesting area of antenna metrology
- To leave the readers with some metrology-related issues for contemplation
- To share some work done in this area

Contents

- Antenna measurement ranges, gain measurement methods
- Elementary ideas of uncertainty and its evaluation
- Uncertainty in horn gain measurements/calibration
- Modified three-antenna gain measurement method
- Outlook
- References/Bibliography

Antenna measurement ranges

- Need a test environment, or range



Antenna range

Reflection range (outdoor)

Free-space range

Outdoor

Indoor

Elevated range

Slant range

Anechoic chamber

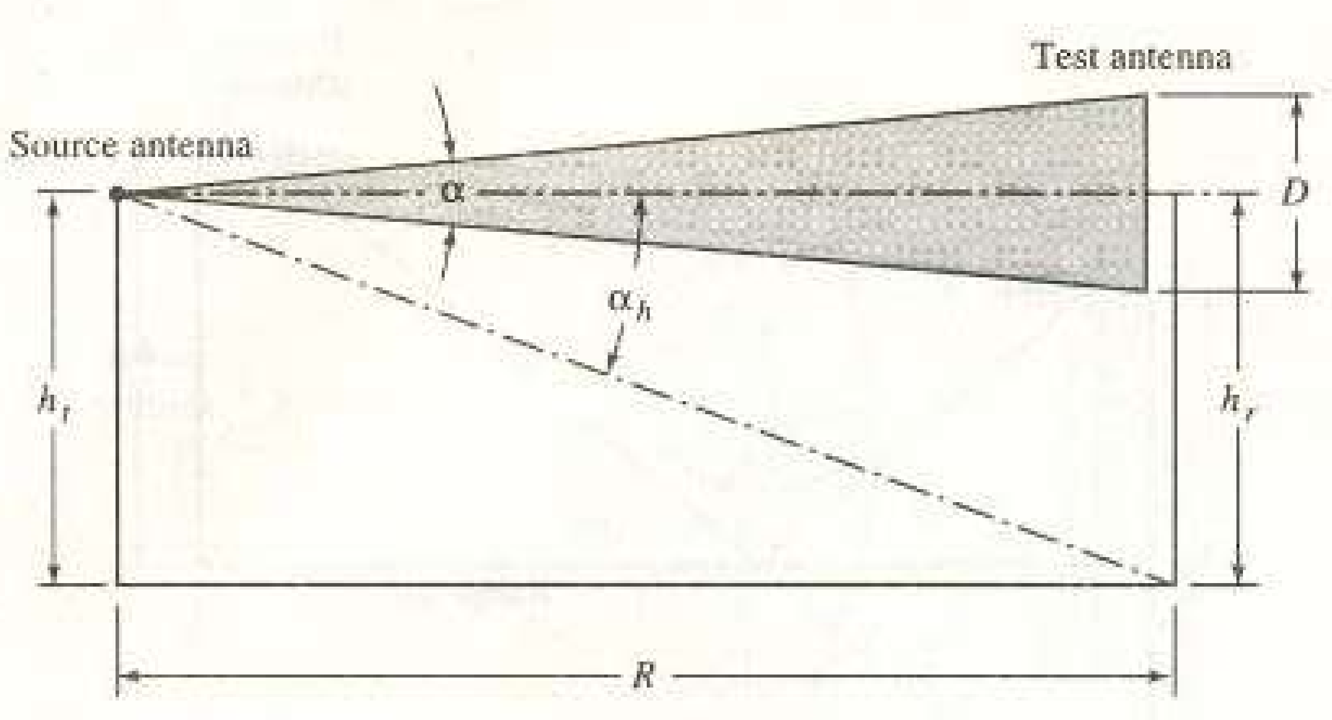
CATR

Near-field range

General measurement challenges

- Ensuring the antennas are in far-field of each other
- Reflections from ground and surrounding objects
- Outdoor ranges weather and environment-dependent
- Enclosed systems present size restrictions
- Building and maintaining generally expensive
- Professional measurements need rigour and hence are tedious

Elevated range

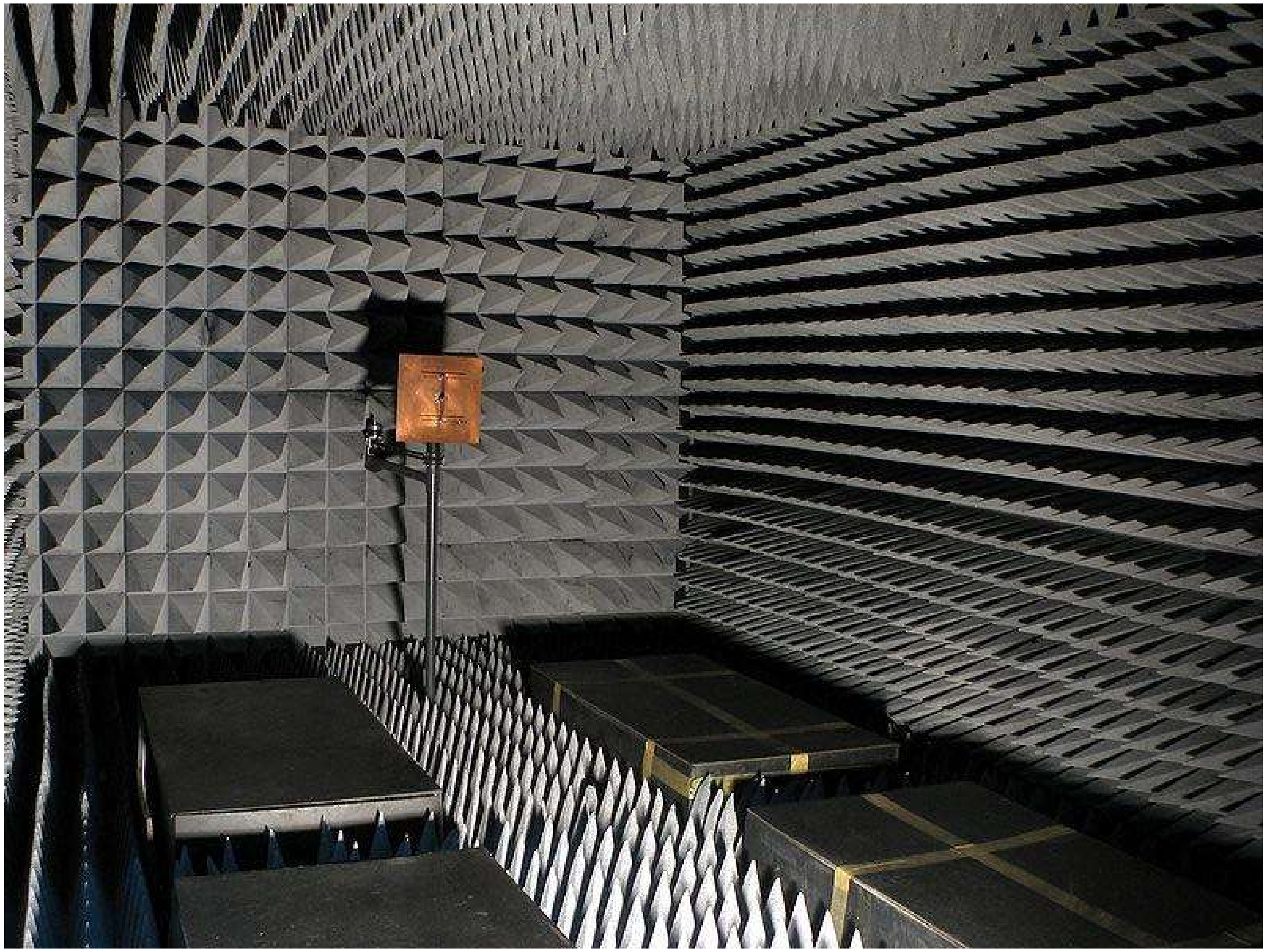


Balanis, p. 842

- Usually on smooth terrains
- Used for testing large antennas
- Interference from surrounding objects reduced by
  - Judicious selection of source antenna pattern
  - Having a clear LOS
  - Redirecting/absorbing signals reflected by obstacles
  - Using signal processing to remove noise from received signal

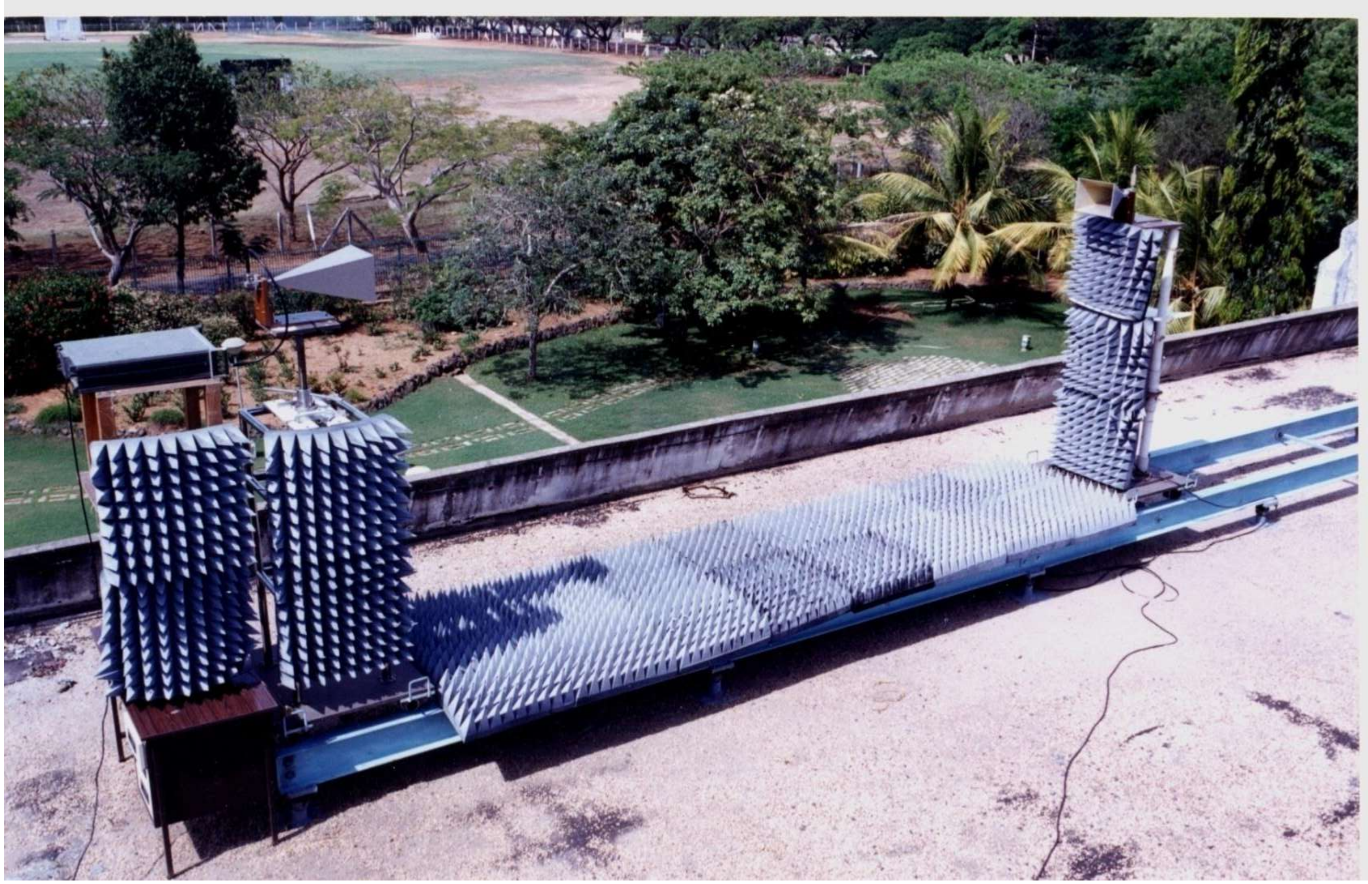
Anechoic chamber

- ‘Free-space’ range
- Advantages:
    - Controlled environment
    - All-weather capability
    - Minimal EMI



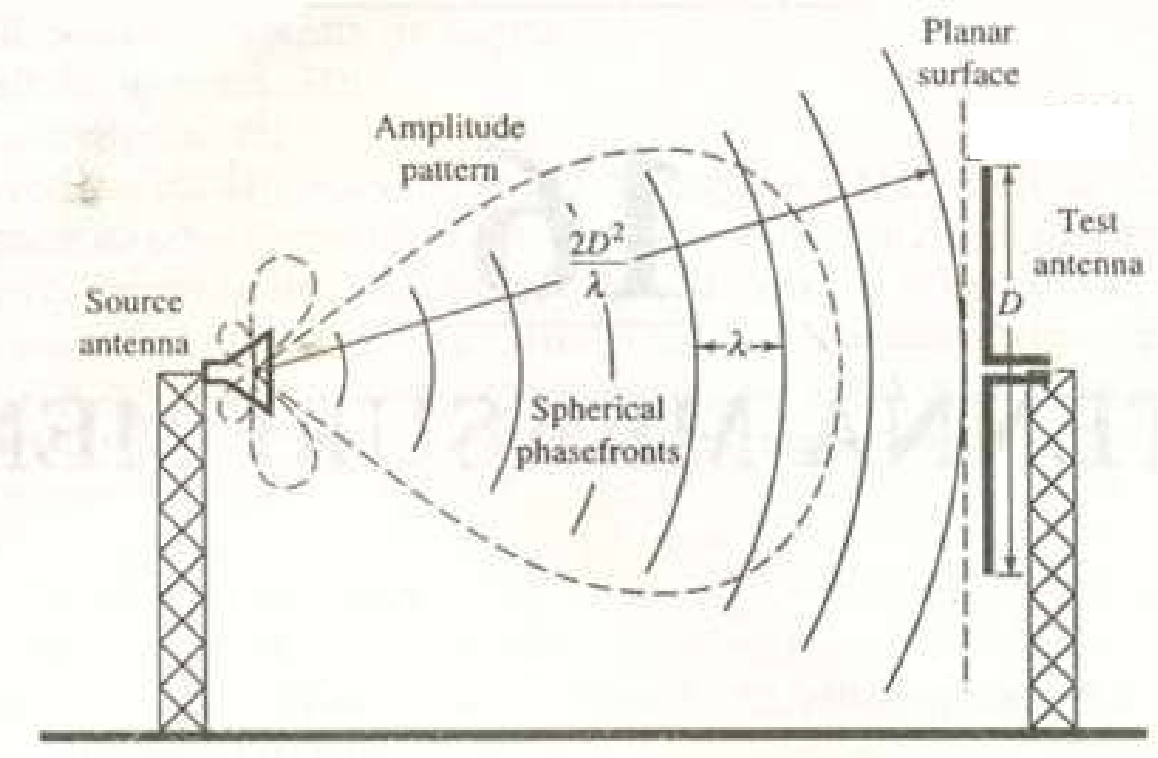
Rectangular anechoic chamber.
http://en.wikipedia.org/wiki/File:Radio-frequency-anechoic-chamber-HDR-oa.jpg

Typical ‘Free-space’ range

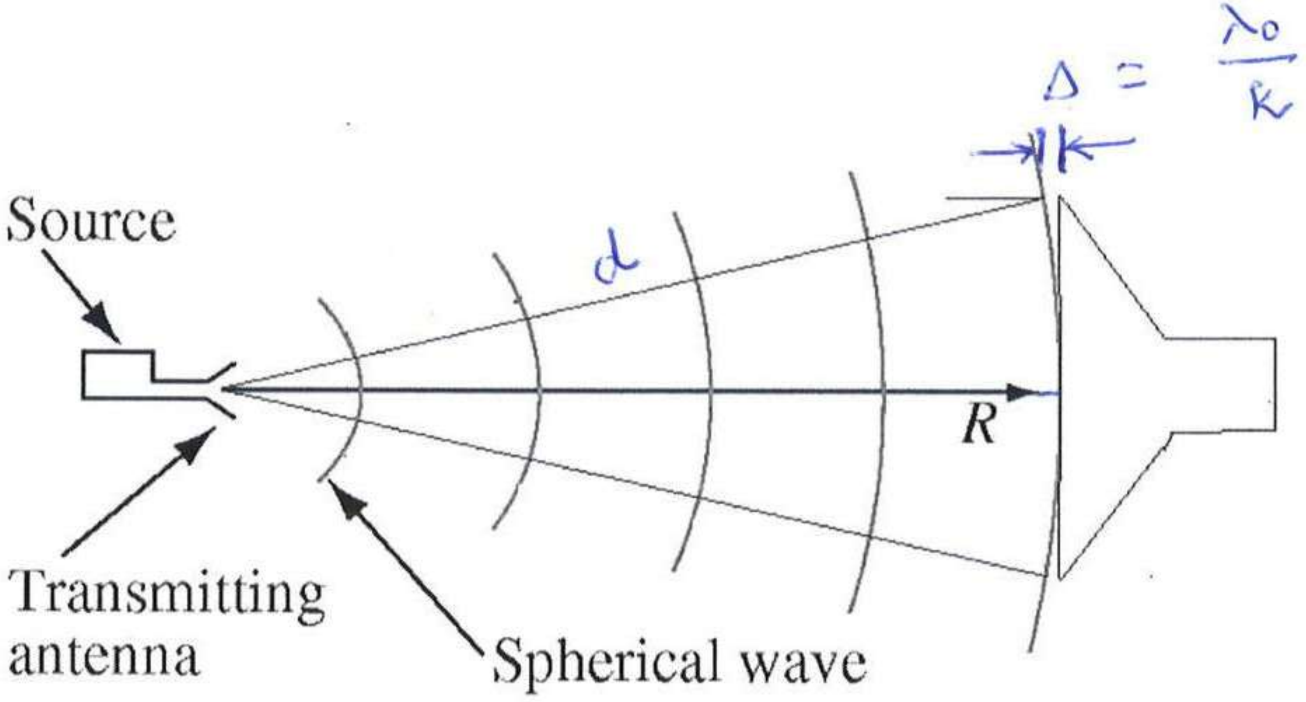


Birail track for antenna testing at SAMEER – Centre for Electromagnetics, Chennai

Far-field criterion



Phase error at the edges of a test antenna in the far-field
when illuminated by a spherical wave
Balanis, p. 840



- Maximum dimension of receiving antenna = D

- Incident plane wave to deviate from planarity only by fraction of wavelength:

$$\Delta = \frac{\lambda_o}{k}, k >> 1$$

- From the geometry,

$$d^2 = (d-\Delta)^2 + \left(\frac{D}{2}\right)^2 = d^2 - 2\Delta d + \Delta^2 + \frac{D^2}{4}$$

$$\approx d^2 - 2d\Delta + \frac{D^2}{4}$$

$$d \approx \frac{D^2}{8\Delta} = \frac{kD^2}{8\lambda_o} \Rightarrow \boxed{d_{far} = \frac{2D^2}{\lambda}} \qquad \text{(with } k = 16\text{)}$$

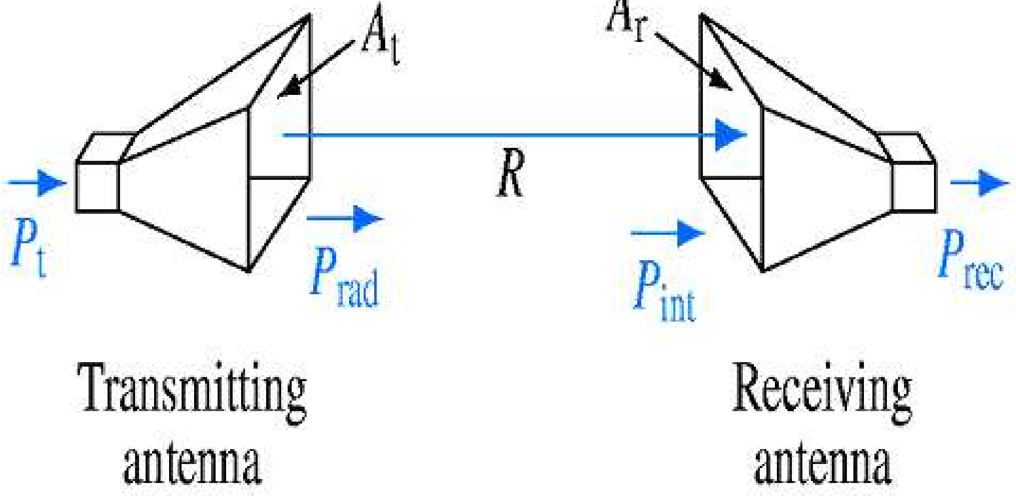
Friis Transmission Formula

- Basis of gain measurement techniques
- Power density radiated by an isotropic antenna:

$$S_{av} = \frac{P_t}{4\pi R^2}$$

For an arbitrary transmit antenna with gain G_t:

$$S_{av} = \frac{G_t P_t}{4\pi R^2}$$



Ulaby, p. 395

Received power:

$$P_r = A_e S_{av} = \frac{G_t P_t A_e}{4\pi R^2}$$

Since

$$A_e = \frac{\lambda^2}{4\pi} G_r$$

$$\boxed{P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t}$$

- The above equation is Friis transmission formula

Gain measurement methods

- All methods require power measurements and the use of Friis’ transmission formula
- Two-antenna method
  - Two nominally identical test antennas
- Three-antenna method
  - Three antennas, all can have unknown gains
- Reference antenna method
  - A Tx antenna, test antenna and a reference antenna

Gain measurement

- **Two-antenna method:**

$$(G_{ot})_{\mathrm{dB}} + (G_{or})_{\mathrm{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_r}{P_t}\right)$$

If transmitting and receiving antennas are identical:

$$(G_{ot})_{\mathrm{dB}} = (G_{or})_{\mathrm{dB}} = \frac{1}{2}\left[20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_r}{P_t}\right)\right]$$

- **Three-antenna method**
  - Three measurements made with all combinations of three antennas (a, b, c)

$$(G_a)_{\text{dB}} + (G_b)_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{rb}}{P_{ta}}\right)$$

$$(G_a)_{\text{dB}} + (G_c)_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{rc}}{P_{tb}}\right)$$

$$(G_b)_{\text{dB}} + (G_c)_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{rc}}{P_{tb}}\right)$$

  - G_a, G_b and G_c can all be found

- **Gain-transfer (Gain comparison) method:**
  - Most commonly used
  - With the same transmitting antenna and maintaining intact the geometrical arrangement,
    - use the test antenna as receiving antenna and record the received power (P_T)
    - replace the test antenna by the reference antenna and record the received power (P_S)
    - Then:

$$(G_T)_{dB} = (G_S)_{dB} + 10\log_{10}\left(\frac{P_T}{P_S}\right)$$

Aspects to be considered

- Frequency stability
- Antennas to be in the far-field of each other
- Boresight alignment of antennas
  - Mechanical and electrical
- Impedance and polarization matching of all components
- Minimal proximity effects and multi-path interference

- System disturbance during replacement of antennas to be minimized
- If test and standard antennas are somewhat similar, method less affected by proximity effects and multipath interference
- Impedance mismatches can be corrected by making complex reflection coefficient measurements

Unavoidable limitations in gain measurements

- There is no perfect measurement!
- *Doubt* about (any) measurement result unavoidable
- The doubt can be reduced, but never eliminated!
- Uncertainty provides a measure of this doubt, and has to generally form part of reporting measurements

Uncertainty and its evaluation: Elementary ideas

- Uncertainty of measurement:
  - Inevitable doubt that exists about **any** measurement result
  - Needs two numbers to be expressed- *Interval*, or *width*, of the margin and *confidence level*
  - *Example*: Test antenna gain is 16 dB ± 0.3 dB with a confidence level of 95%
  - Speaks about the quality of the measurement

- Interesting questions:
  - Can the ‘true’ value of a measurand be known?
  - Can the limits of uncertainty be known with *certainty*?
  - Is error same as uncertainty?
- Sources of uncertainties:
  - Instruments/calibration
  - Item under test
  - Measurement process
  - Operator skill
    - Mistakes?
  - Sampling issues
  - Environment

- Estimating uncertainty:
  - Type A evaluation (done by employing statistical methods)
  - Type B evaluation (arrived at from other information)
- Other terms:
  - Accuracy
    - Closeness between the measured value and the value of the measurand
    - A qualitative concept
  - Repeatability – same conditions of measurements
  - Reproducibility - changed conditions of measurements
    - Inter-lab comparison of measurements desired
      - SAMEER and UNMC

Uncertainty evaluation in antenna measurements

- Some sources of uncertainty/error [1]:
  - Proximity correction
  - Random effect
  - Multipath propagation
  - Power meter/source
  - Mismatch
  - Antenna alignment

Proximity Correction

- Conventional far-field criterion only an approximation

- Chu and Semplak [2] suggested necessary corrections for horn antennas can be estimated by taking the ratio between finite-range and far-field gains

- They expressed the correction as

$$C = (G / G_N) = C_E C_H$$

with C_E and C_H computed numerically using the equations in [2]

Random Effect

- Accounts for the errors due to equipment stability, antenna alignment, waveguide alignment with horn antenna, cable and connector repeatability etc [3].
- Estimated by taking standard deviation of ‘n’ samples of measured values, for n separations, at each frequency using,

$$\sigma_R = \sqrt{\frac{\sum_{i=1}^{n} (G_i - \overline{G})^2}{n-1}}$$

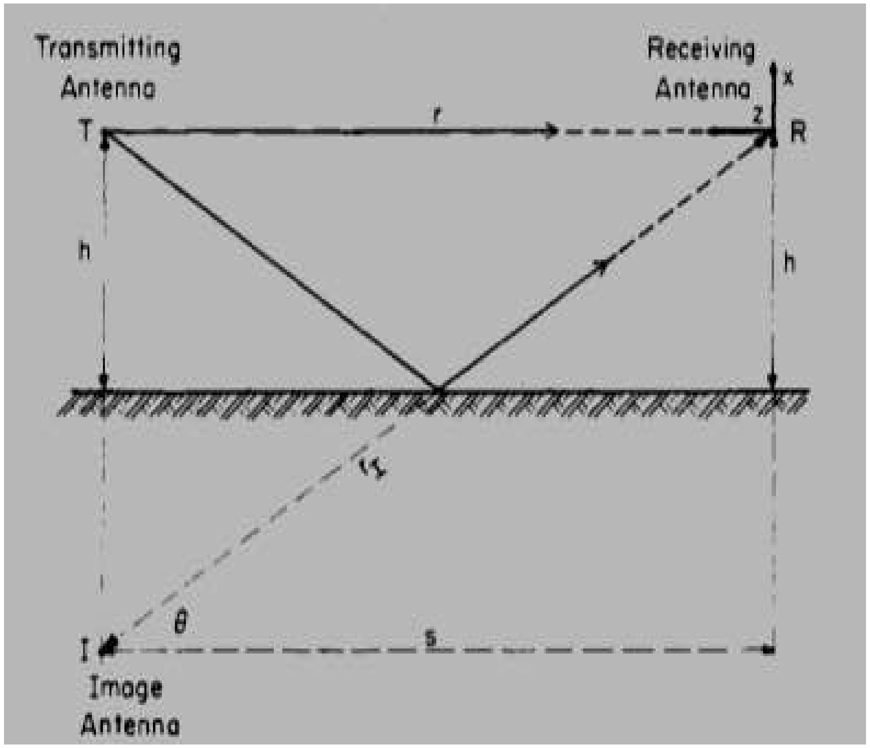
where G_i – gain value of i^{th} sample

$\overline{G}$ – mean value of the ‘n’ samples

n – number of samples

Multipath Effect

- To a good approximation, can be eliminated by averaging measurements at a large number of separations ([4] & [5])



Multipath Interference Illustration [4]

- Actual situation much more complicated!

Mismatch

- Can be corrected for by using
  - measured reflection coefficients of the antennas under test,
  - manufacturer-provided values for the generator & load
- Even then there is possibility of uncertainty σ_{MM} in this type of corrections
- A conservative criterion is employed for the uncertainty in this case ([1] & [3])
  - Typical uncertainty value 0.03dB

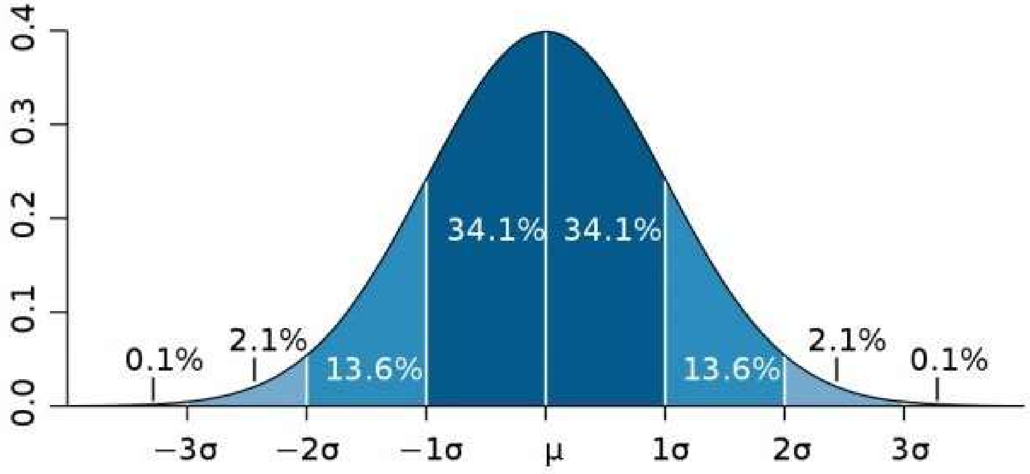
Power Meter Uncertainty

- Generally quoted by manufacturer
- Represented by σ_{PM}
- Typical value of power meter uncertainty is 0.07 dB

Combined Uncertainty

- The combined uncertainty can be estimated by taking root mean square value of all possible uncertainty values:

$$\sigma_{CU} = \sqrt{\sigma_{R}^{2} + \sigma_{MM}^{2} + \sigma_{PM}^{2}}$$



Uncertainty	Confidence level
1σ	68.2%
2σ	95.4%
3σ	99.6%

ILLUSTRATION

Uncertainty estimation of 4.8 – 11 GHz ridged horn

- Two-antenna method employed
- $n = 10$
- Frequency step = 20 MHz
- 10 separations: 3.5 m to 7.5 m, 0.5 m step

Estimated Gains

- Average gain values for each separation

f, GHz	Gain, dB, at an antenna separation, in metre, of									
	3	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**
4.8	13.2068	13.1448	13.3427	13.3402	13.3418	13.4772	13.1856	13.7242	13.3611	13.6732
5	12.8997	12.3981	12.548	12.7851	12.6836	12.8081	12.202	13.3456	12.9039	13.4916
6	15.3567	15.0692	15.3466	15.2711	15.4172	15.1536	14.951	15.7891	15.4345	15.7261
7	17.7744	18.1994	18.2128	18.1463	18.1769	18.2968	18.2217	18.8548	18.6707	18.7148
8	19.4525	19.462	19.5669	19.66	19.735	19.7555	19.7088	20.039	19.8983	19.9214
9	20.162	20.0324	20.1123	20.3194	20.3619	20.5879	20.4663	20.4364	20.3582	20.5489
10	20.4852	20.3072	20.3081	20.7251	20.8212	20.9752	20.905	20.8307	20.7795	20.8701
11	20.0351	19.7936	19.863	19.999	20.0331	20.212	20.1094	20.245	20.2094	20.33

Proximity Corrections

f, GHz	Correction in dB, at an antenna separation, in metre, of									
	3	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**
4.8	0.1252	0.1058	0.0916	0.0807	0.0721	0.0652	0.0595	0.0547	0.0506	0.0471
5	0.1356	0.1146	0.0992	0.0875	0.0782	0.0707	0.0645	0.0593	0.0548	0.051
6	0.1936	0.1638	0.1419	0.1251	0.1119	0.1012	0.0923	0.0849	0.0786	0.0731
7	0.2608	0.2209	0.1915	0.169	0.1512	0.1368	0.1249	0.1149	0.1063	0.099
8	0.3363	0.2852	0.2476	0.2186	0.1957	0.1772	0.1618	0.1489	0.1379	0.1284
9	0.4193	0.3562	0.3095	0.2736	0.2451	0.222	0.2028	0.1867	0.1729	0.1611
10	0.5086	0.4327	0.3766	0.3332	0.2987	0.2707	0.2475	0.2279	0.2112	0.1968
11	0.603	0.5141	0.448	0.3968	0.3561	0.3229	0.2954	0.2722	0.2523	0.2352

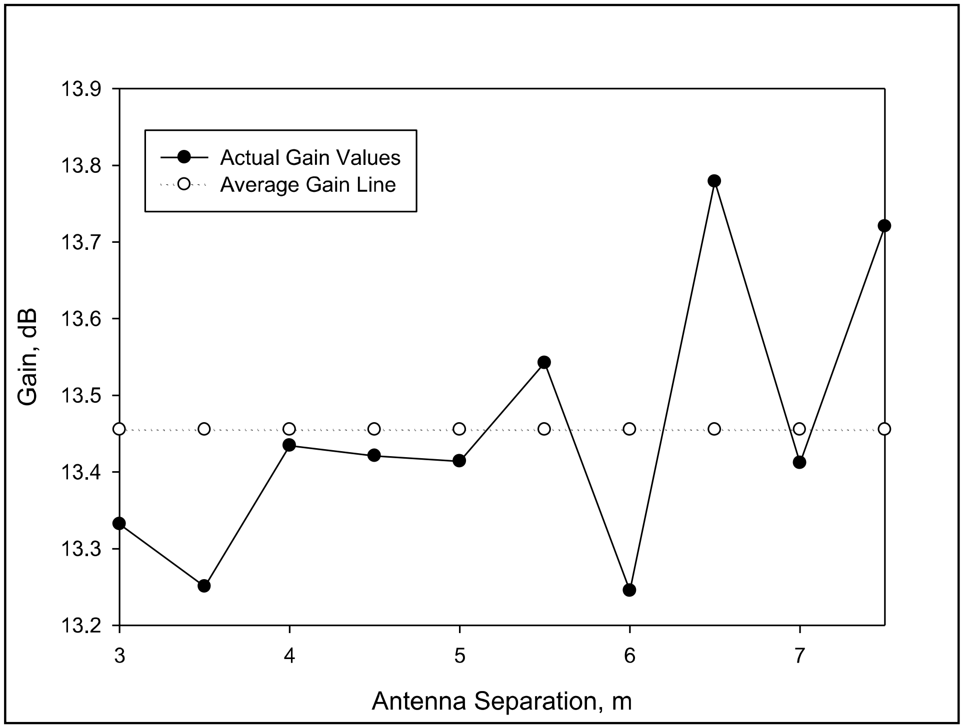
Proximity Corrected Gains

f, GHz	Corrected gain in dB, at an antenna separation, in metre, of										Proximity corrected average gain, dB
	3	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**	
4.8	13.332	13.2506	13.4343	13.4209	13.4139	13.5424	13.2451	13.7789	13.4117	13.7203	13.45501
5	13.0353	12.5127	12.6472	12.8726	12.7618	12.8788	12.2665	13.4049	12.9587	13.5426	12.88811
6	15.5503	15.233	15.4885	15.3962	15.5291	15.2548	15.0433	15.874	15.5131	15.7992	15.46815
7	18.0352	18.4203	18.4043	18.3153	18.3281	18.4336	18.3466	18.9697	18.777	18.8138	18.48439
8	19.7888	19.7472	19.8145	19.8786	19.9307	19.9327	19.8706	20.1879	20.0362	20.0498	19.9237
9	20.5813	20.3886	20.4218	20.593	20.607	20.8099	20.6691	20.6231	20.5311	20.71	20.59349
10	20.9938	20.7399	20.6847	21.0583	21.1199	21.2459	21.1525	21.0586	20.9907	21.0669	21.01112
11	20.6381	20.3077	20.311	20.3958	20.3892	20.5349	20.4048	20.5172	20.4617	20.5652	20.45256

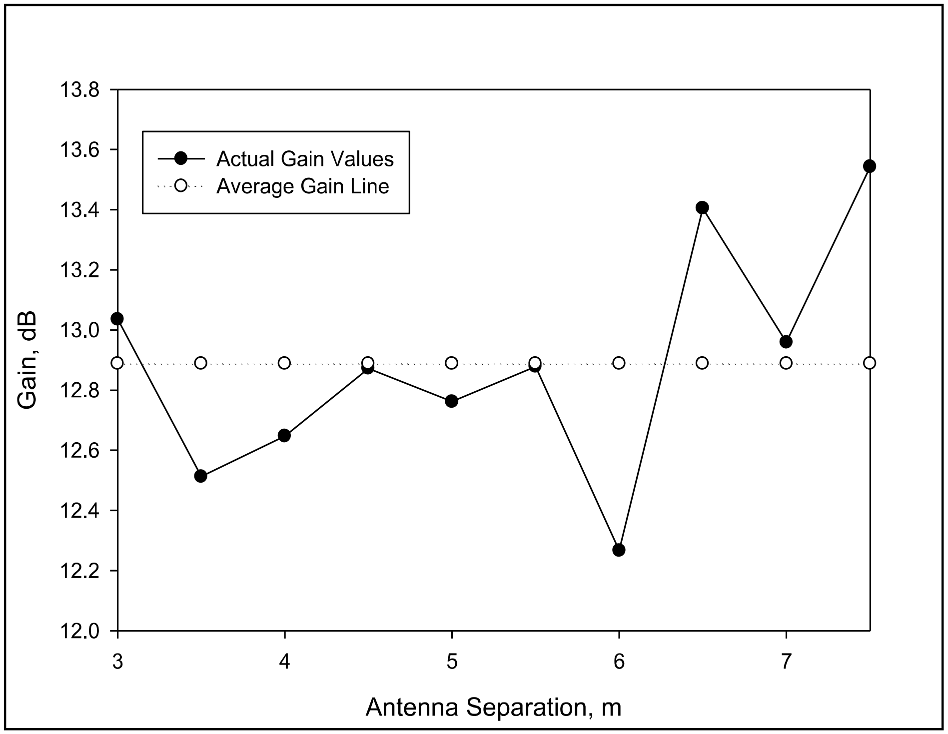
Random Effect

f, GHz	Standard deviation, at an antenna separation, in metre, of										Uncertainty due to random effect in dB
	3	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**	
4.8	0.040838	0.059069	0.013427	0.128894	0.064397	0.165727	0.074276	0.069292	0.089513	0.04714	0.07525735
5	0.040308	0.090445	0.029387	0.058737	0.101154	0.297023	0.128954	0.059584	0.150185	0.067132	0.102290898
6	0.077165	0.051435	0.025326	0.312297	0.235641	0.148867	0.089449	0.04295	0.073417	0.103891	0.1160437
7	0.020303	0.017488	0.011106	0.047598	0.018135	0.03653	0.030092	0.023857	0.021915	0.030894	0.025791909
8	0.006992	0.014103	0.010488	0.047037	0.010541	0.034404	0.021499	0.013834	0.027909	0.011891	0.019869772
9	0.016125	0.010541	0.003333	0.056591	0.011414	0.02993	0.013784	0.019923	0.031398	0.011068	0.020410728
10	0.013904	0.011068	0.010865	0.057116	0.009443	0.037197	0.030097	0.01355	0.016168	0.034436	0.023384418
11	0.013081	0.020843	0.016029	0.045228	0.016508	0.031096	0.021628	0.020656	0.028191	0.017552	0.02308113

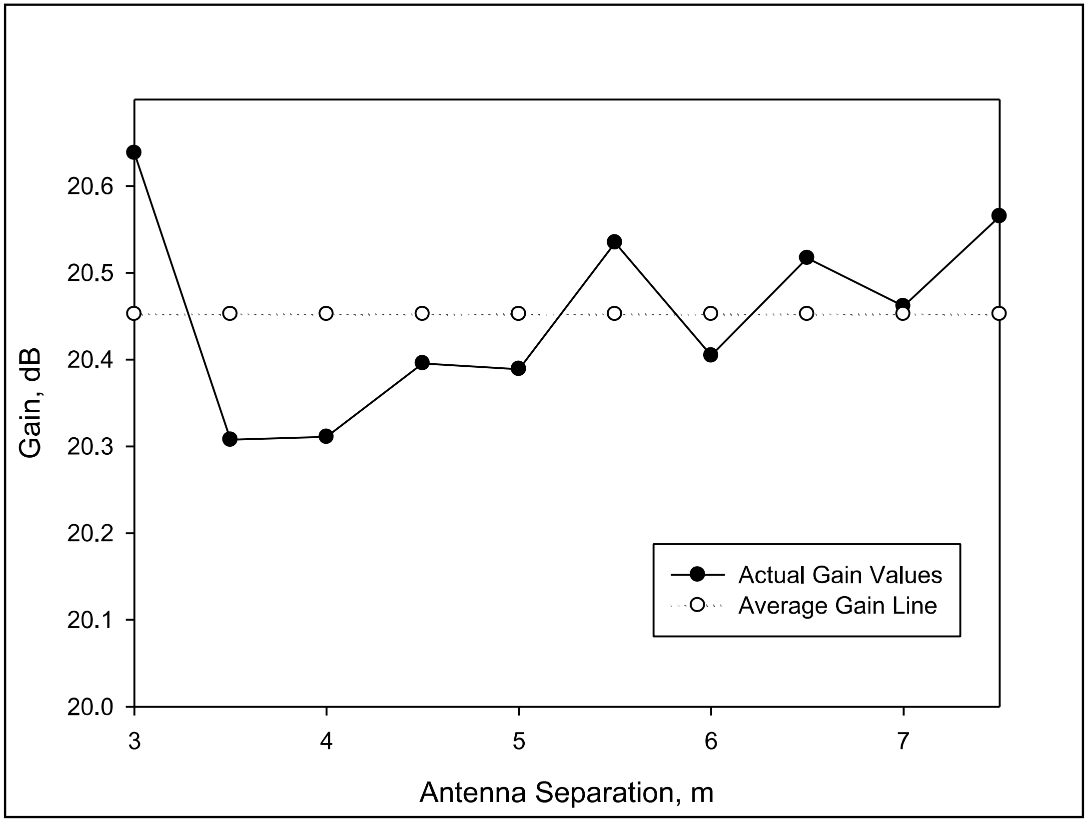
Multipath Effect



$f = 4.8\,\text{GHz}$



$f = 5\,\text{GHz}$


Gain, dB
20.0
20.1
20.2
20.3
20.4
20.5
20.6
3
4
5
6
7
Antenna Separation, m
Actual Gain Values
Average Gain Line

$$f = 11\text{GHz}$$

Combined Uncertainty

f, GHz	Average, mismatch and proximity-corrected gain value, in dB, at separation (m)										Average gain (removes multipath effect), dB	Random uncertainty, dB	Mismatch uncertainty (others), dB	Power meter uncertainty, dB	Combined uncertainty, dB (3σ)
	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5					
4.8	13.332	13.2506	13.4343	13.4209	13.4139	13.5424	13.2451	13.7789	13.4117	13.7203	13.45501	0.07525735	0.03	0.07	0.32120557
5	13.0353	12.5127	12.6472	12.8726	12.7618	12.8788	12.2665	13.4049	12.9587	13.5426	12.88811	0.102290898	0.03	0.07	0.382584436
6	15.5503	15.233	15.4885	15.3962	15.5291	15.2548	15.0433	15.874	15.5131	15.7992	15.46815	0.1160437	0.03	0.07	0.416407569
7	18.0352	18.4203	18.4043	18.3153	18.3281	18.4336	18.3466	18.9697	18.777	18.8138	18.48439	0.025791909	0.03	0.07	0.241219823
8	19.7888	19.7472	19.8145	19.8786	19.9307	19.9327	19.8706	20.1879	20.0362	20.0498	19.9237	0.019869772	0.03	0.07	0.236121305
9	20.5813	20.3886	20.4218	20.593	20.607	20.8099	20.6691	20.6231	20.5311	20.71	20.59349	0.020410728	0.03	0.07	0.236536214
10	20.9938	20.7399	20.6847	21.0583	21.1199	21.2459	21.1525	21.0586	20.9907	21.0669	21.01112	0.023384418	0.03	0.07	0.239001003
11	20.6381	20.3077	20.311	20.3958	20.3892	20.5349	20.4048	20.5172	20.4617	20.5652	20.45256	0.02308113	0.03	0.07	0.238735517

Uncertainty estimation challenges

- A demanding task
- “Statistics is an art with a lot of room for creativity and mistakes” - John Tsitsiklis, the Clarence J. Lebel Professor of Electrical Engineering, MIT
- Financial, manpower and other impediments
- Methods facilitating simplified uncertainty estimation desirable

Comments on reference antenna method

- Standard antenna assumed to offer its reference gain values in the given test environment
- Should it necessarily be the case?
- An alternative method?

Modified three-antenna gain estimation method

- Proposed in [6] to simplify uncertainty estimation
- One of the three antennas is a reference antenna
- Measurements made as in three-antenna method
- Comparison between measured and manufacturer-supplied values for the reference antenna provides an estimate of <u>error</u> in measurements

Outlook

- Metrology – an interesting, challenging area
- Uncertainty – a technically, philosophically enjoyable topic
- Methods that simplifying uncertainty estimation in measurements important

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2. S. Bell, “A beginner’s guide to uncertainty of measurement,” *NPL Measurement Good Practice Guide* No. 11, Issue 2, 1999

Uncertainty in horn antenna measurements:

3. K. T. Selvan, “A modified three-antenna gain measurement method to simplify uncertainty estimation,” *Progress in Electromagnetics Research* , vol. 57, 197-208, 2006

4. K.T. Selvan, “Preliminary examination of a modified three-antenna gain-measurement method to simplify uncertainty estimation,” *IEEE Antennas and Propagation Magazine*, vol. 45, no. 2, April 2003, pp. 78 – 81

6. K.T. Selvan, V. Venkatesan and R. Sivaramakrishnan, “Uncertainty analysis for the three-antenna gain measurement method,” *Proceedings of International Conference on Electromagnetic Interference and Compatibility*, 2003, pp. 297 - 300

7. K.T. Selvan, “A revisit of the reference antenna gain measurement method,” *Proceedings of International Conference on Electromagnetic Interference and Compatibility*, 2006, pp. 467 - 469

8. K.T. Selvan, R. Sivaramakrishnan, K.R. Kini, and D.R. Poddar, “Experimental verification of the generalized Schedlkunoff’s horn-gain formulas for sectoral horns,” *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 6, June 2002, pp. 875-877

9. C.F. Studenrauch, et al., “International intercomparison of horn gain at X-band,” *IEEE Transactions on Antennas and Propagation*, vol. 44, no. 19, Oct. 1996, pp. 1367-1374

Summary

- Antenna gain measurement methods
- Uncertainty in gain measurement
- Contributing factors
- Estimating uncertainty
- Illustration

Acknowledgements

- V. Lingasamy, Research Student
- SAMEER – Centre for Electromagnetics

Uncertainty in Pattern Measurements: Some Examples and Challenges

Prof. Satish K. Sharma

Director, Antenna and Microwave Laboratory (AML)

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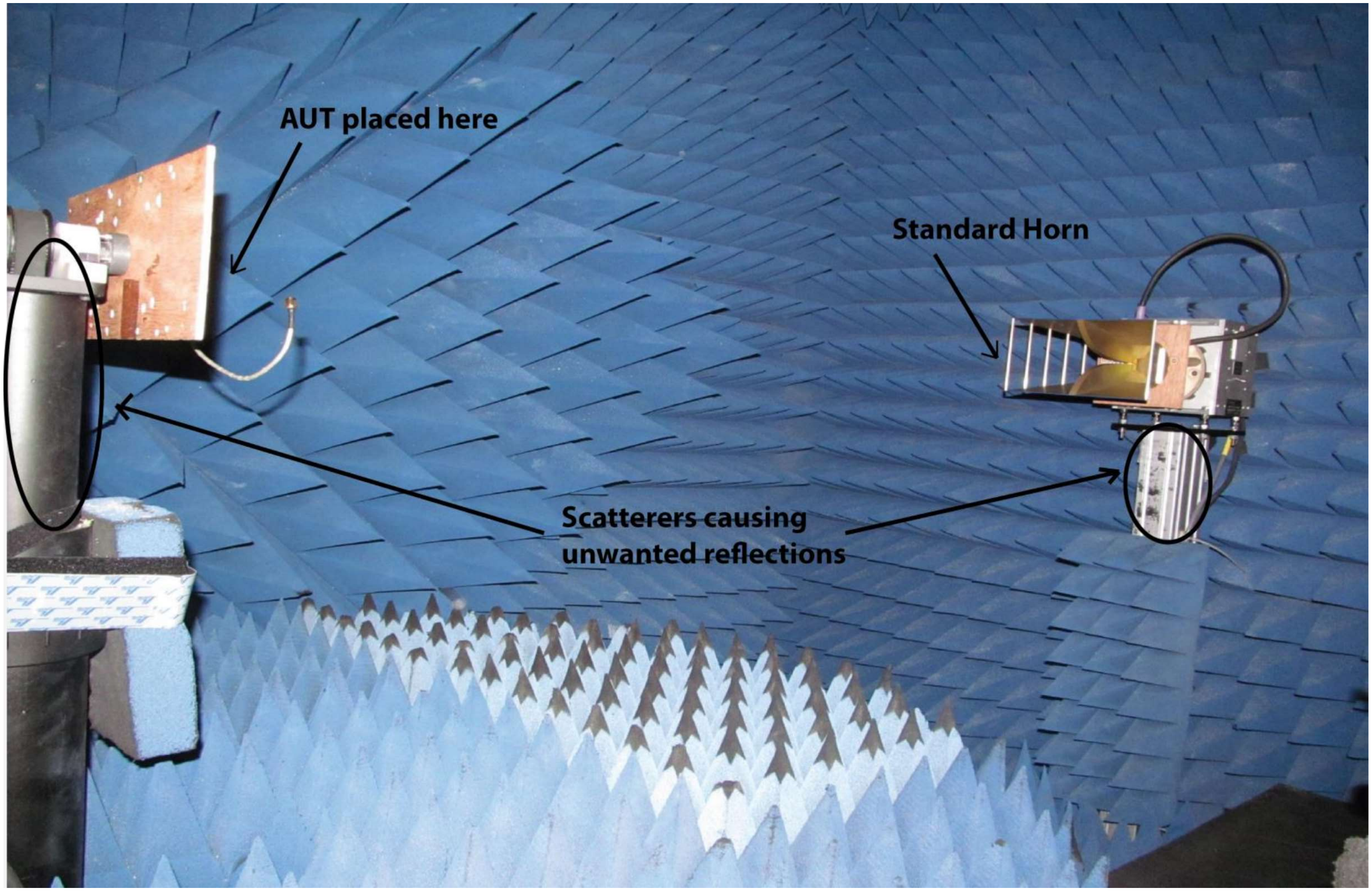
Website: http://electrical.sdsu.edu/faculty/satish/index.html

Anechoic Chamber at AML



- **Antenna positioner and measurement system is supported by Orbit FR**
- **Combined far-field and spherical near-field pattern measurement**
- **Discussion limited to far-field pattern measurement**

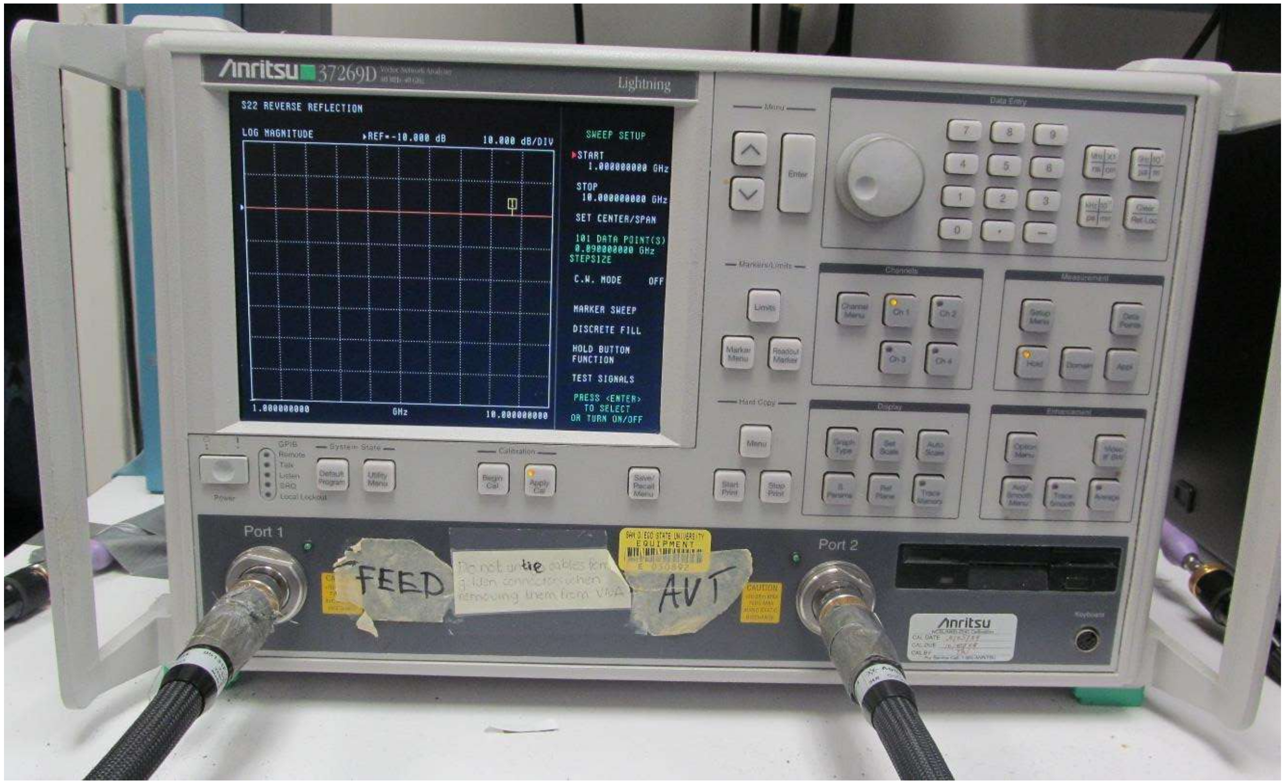
Other Resources at AML

Vector Network Analyzer connected with antenna Orbit FR positioner

Surface Mount Component Soldering Station

LPKF Milling machine

Vector Network Analyzer

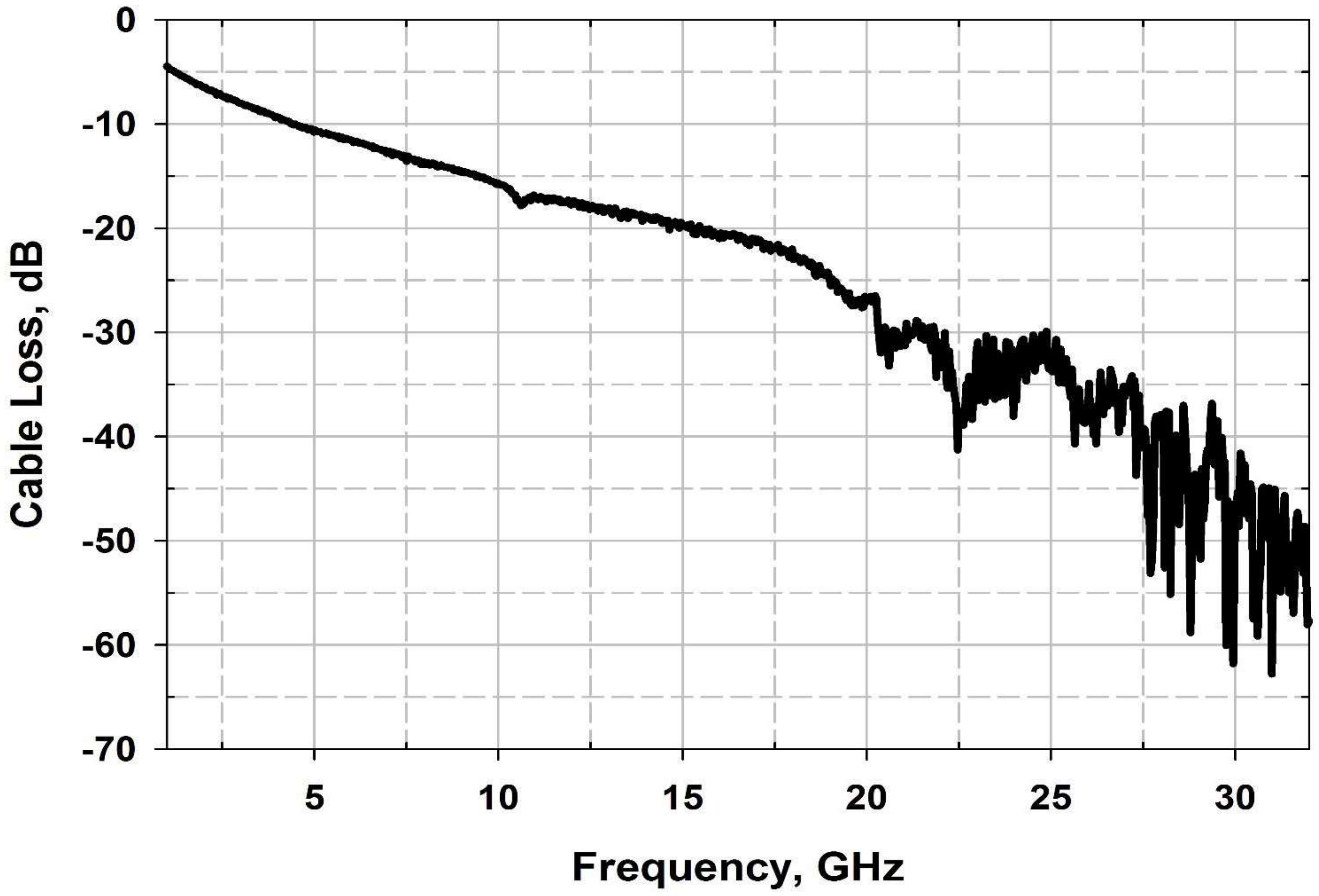


- Anritsu VNA model # 37269D available in AML Lab has maximum operating frequency of 40 GHz
- Dynamic range is -85 dBm so received signal should be higher than this

Challenges in Pattern Measurements

- The VNA goes till 40 GHz but the maximum frequency depends on the available standard Gain Reference Antenna
- The cables going into the anechoic chamber shows a very high attenuation beyond 18 GHz (> 40 dB)
- Free space path loss increases with increasing frequency.
- As a result, it becomes very difficult to get the actual measurement of the AUT operating beyond 18 GHz, as the received signal sometimes goes below the noise floor of the VNA.

Cable Loss (Attenuation)

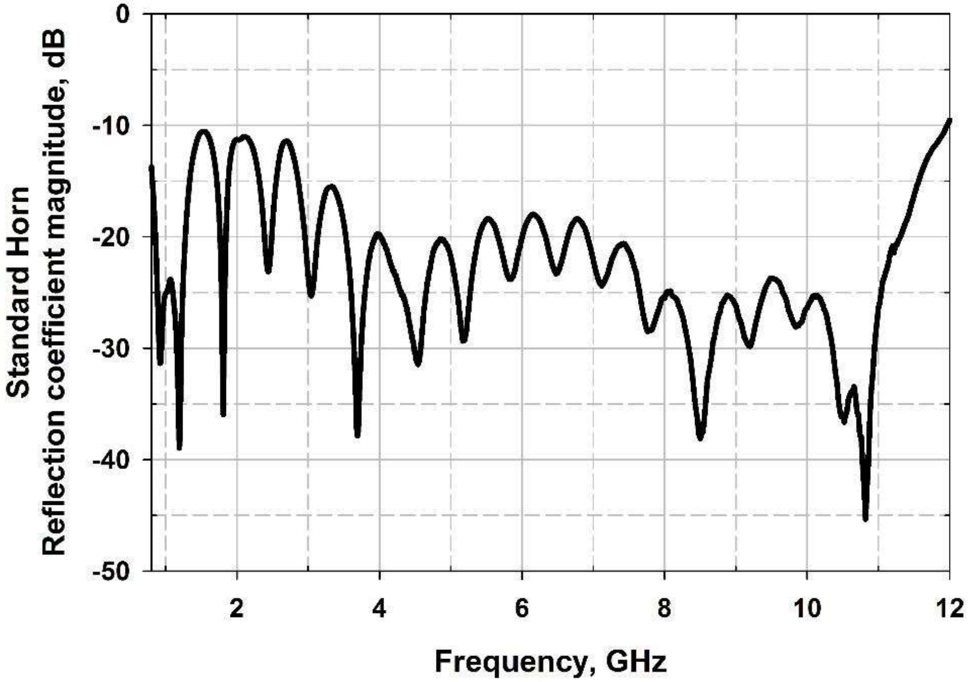


The cable of length approx. 25 feet shows very high attenuation and random fluctuations after around 20 GHz

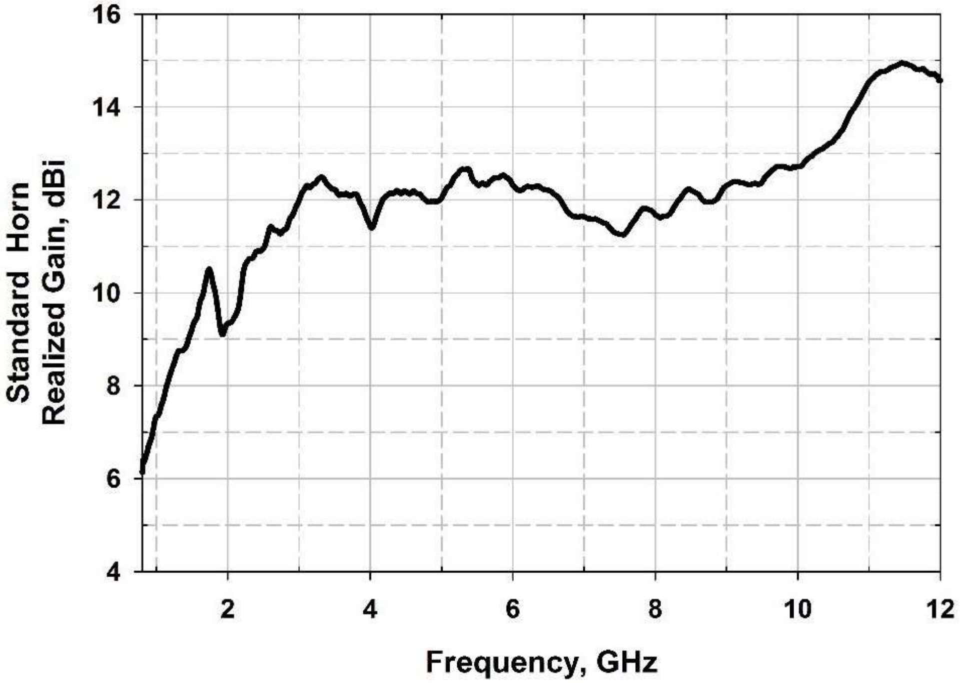
Standard Horn: SATIMO 800MHz – 12GHz

Standard Horn: SATIMO 800MHz – 12GHz

Reflection co-efficient magnitude



Peak Realized Gain

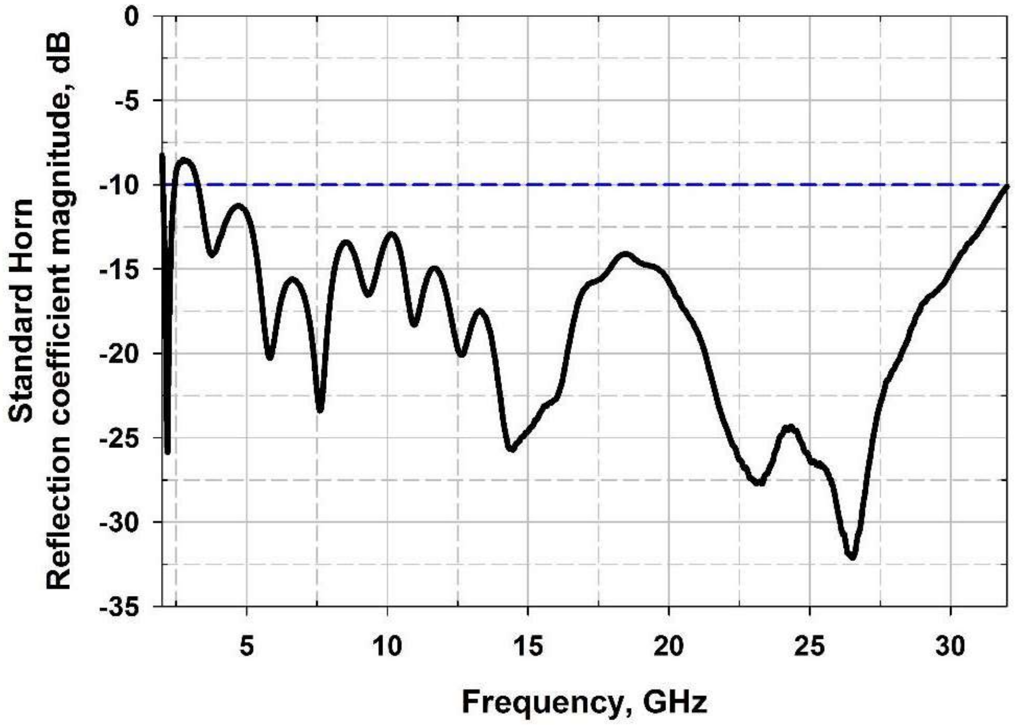


Over the edge of frequency band, the mismatch increases

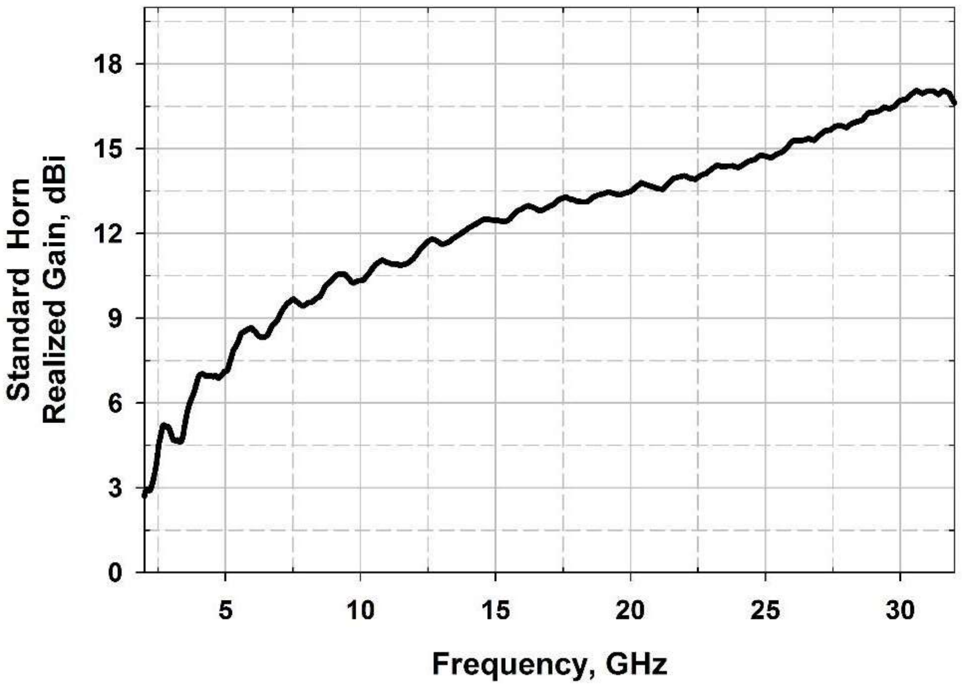
Standard Horn: SATIMO 2GHz – 32GHz

Standard Horn: SATIMO 2GHz – 32GHz

Reflection Co-efficient magnitude



Peak Realized Gain

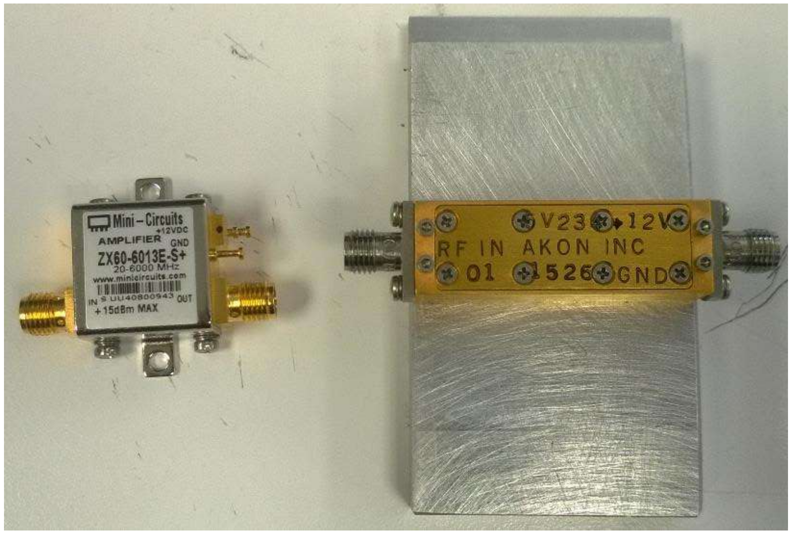


Over the edge of frequency band, the mismatch increases

Possible Solutions for Cable Loss

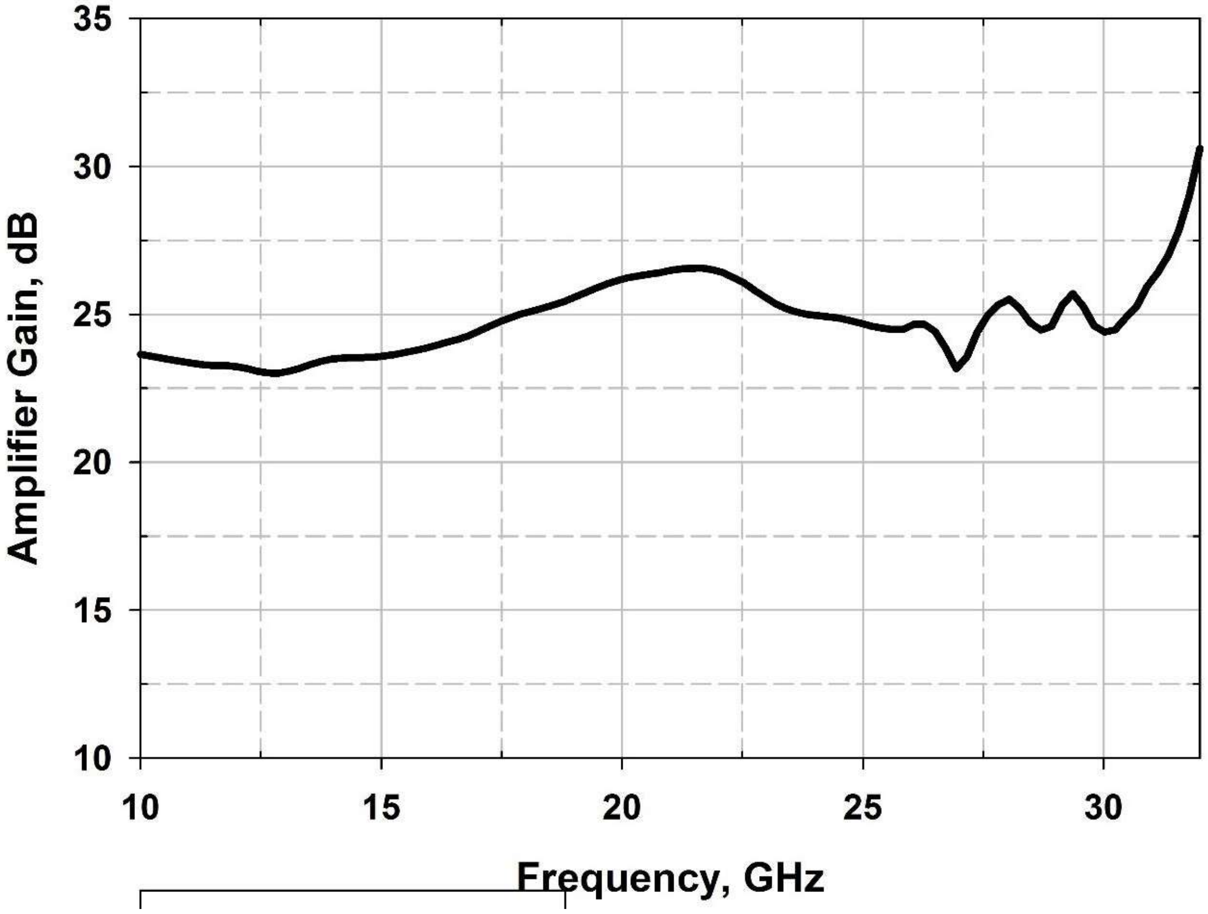
- Replace the cables with a high quality low loss cables which can go till 40 GHz.

- Use a wideband RF power amplifier which can provide high gain (~30 dB) to compensate for the high attenuation of the cables.



- Use time gating approach to remove the effect of scatterers in multi-scattererring environment

Gain of Power Amplifier used as a Solution to Increase the Received Signal Level



Good Quality Cable Specification

Electrical Specifications

- Frequency Range, GHz : DC to 40
- Impedance, Ohms: 50
- Maximum VSWR : 1.38:1
- Insertion Loss @10 GHz: 0.43dB/ft
- Insertion Loss @18 GHz: 0.59dB/ft
- Insertion Loss @26.5 GHz: 0.72dB/ft
- Insertion Loss @40 GHz: 0.9dB/ft

2.92 mm male to 2.92mm male VNA test Cable

SMA Connector vs K(2.92 mm) Connector

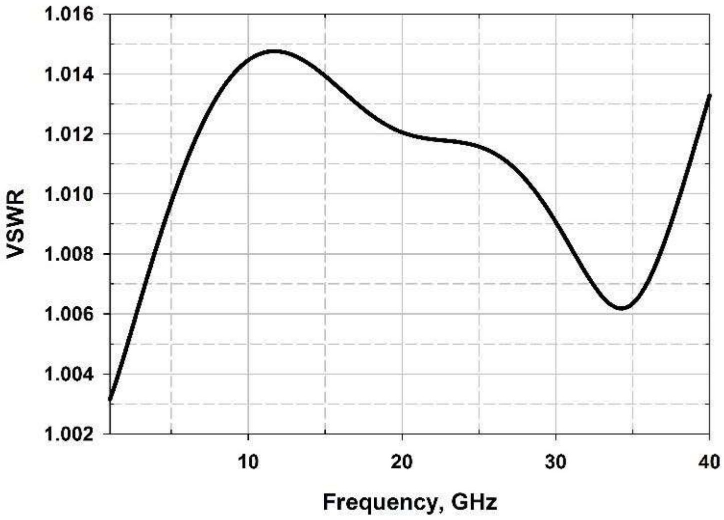
SMA Connector

Electrical Characteristics

1. Frequency Range: DC- 18 GHz
2. Nominal Impedance: 50 Ω
3. VSWR: 1.23 max

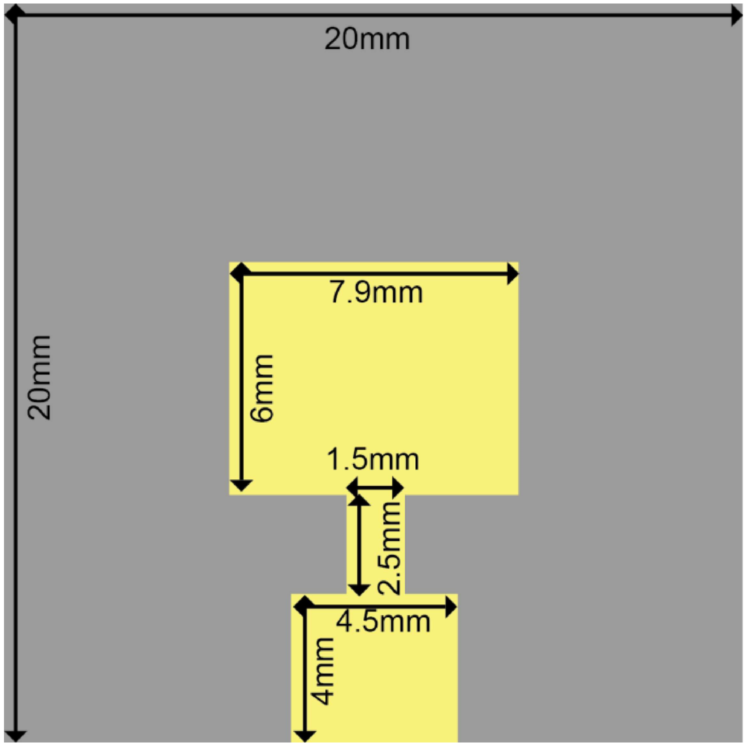
K Connector (2.92 mm connector)

The high performance K connectors feature maximum VSWR for cable connectors of 1.15:1 from DC to 18 GHz, 1.25:1 from 18 to 40 GHz

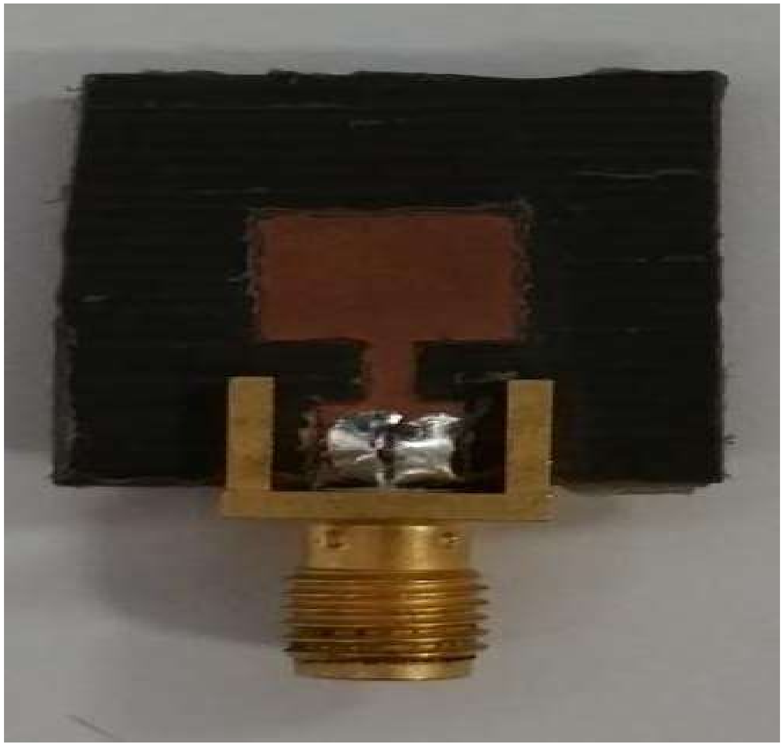


Pattern Measurement: Example 1

Rectangular patch antenna designed at 15 GHz and milled using LPKF Protomat S-42 milling machine available in AML

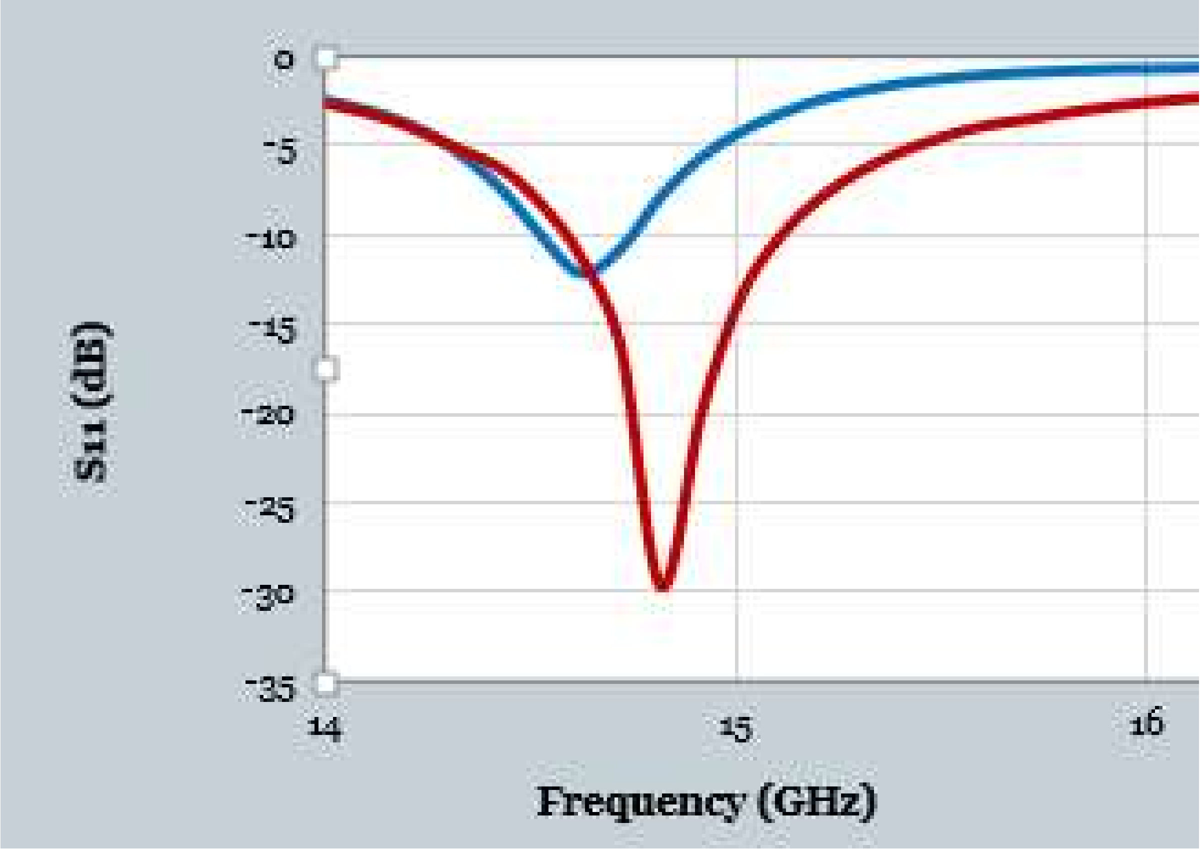


Simulated model on 30 mil Rogers 5880 substrate



Fabricated Antenna with 50 Ohm SMA

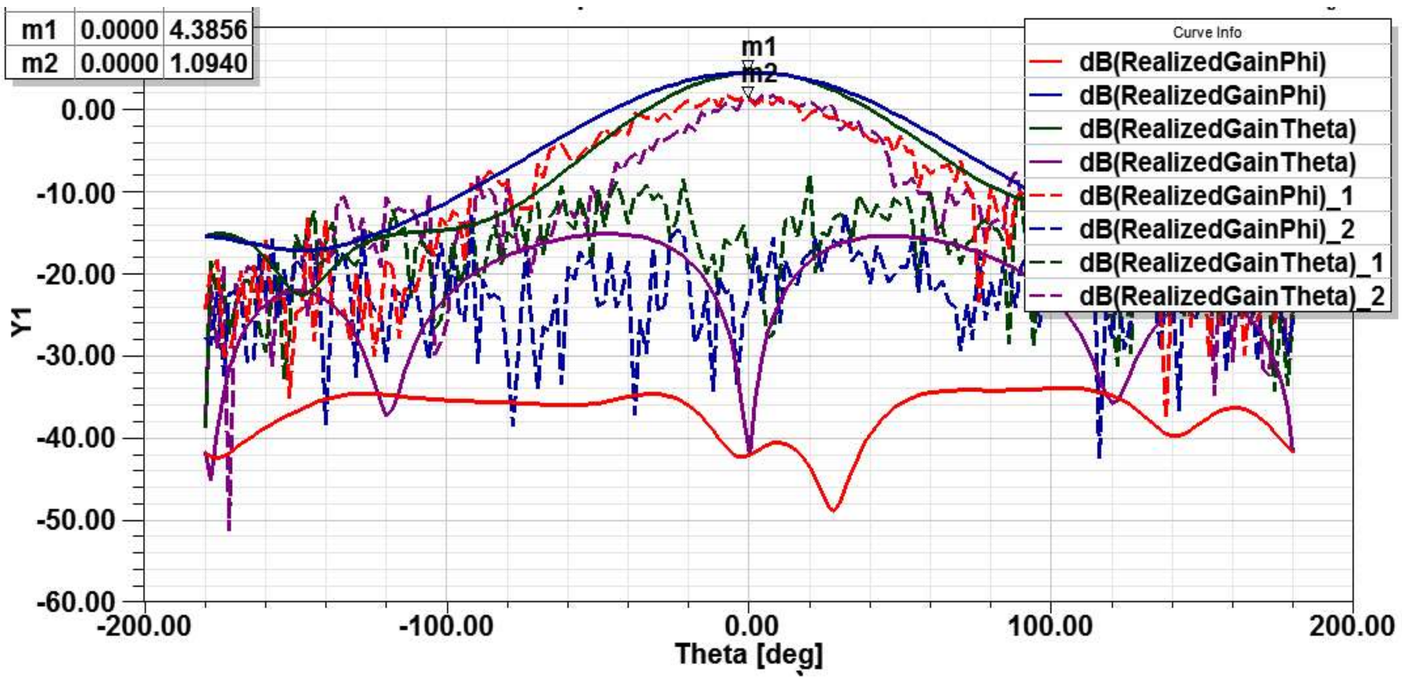
Reflection Coefficient Magnitude



red – simulated scattering parameter and blue – measured scattering parameter

Slight Shift in measured impedance matching is due to fabrication imperfections considering milling bit size accuracy and SMA

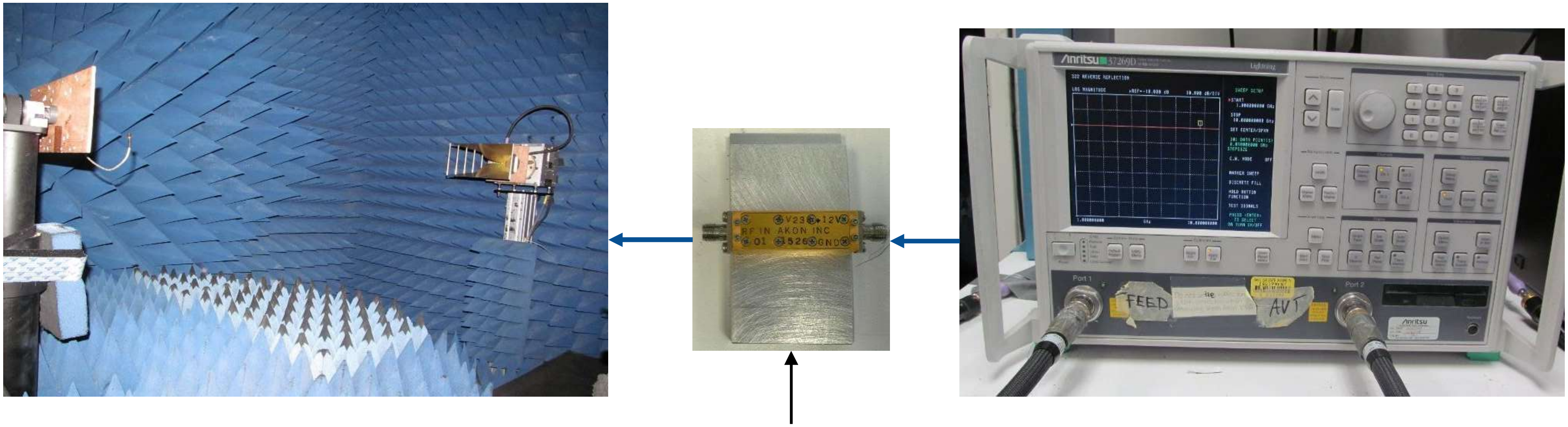
Pattern Measured without using Amplifier



Solid lines: Simulated co and cross-pol radiation components
Dashed lines: Measured co- and cross-pol radiation components

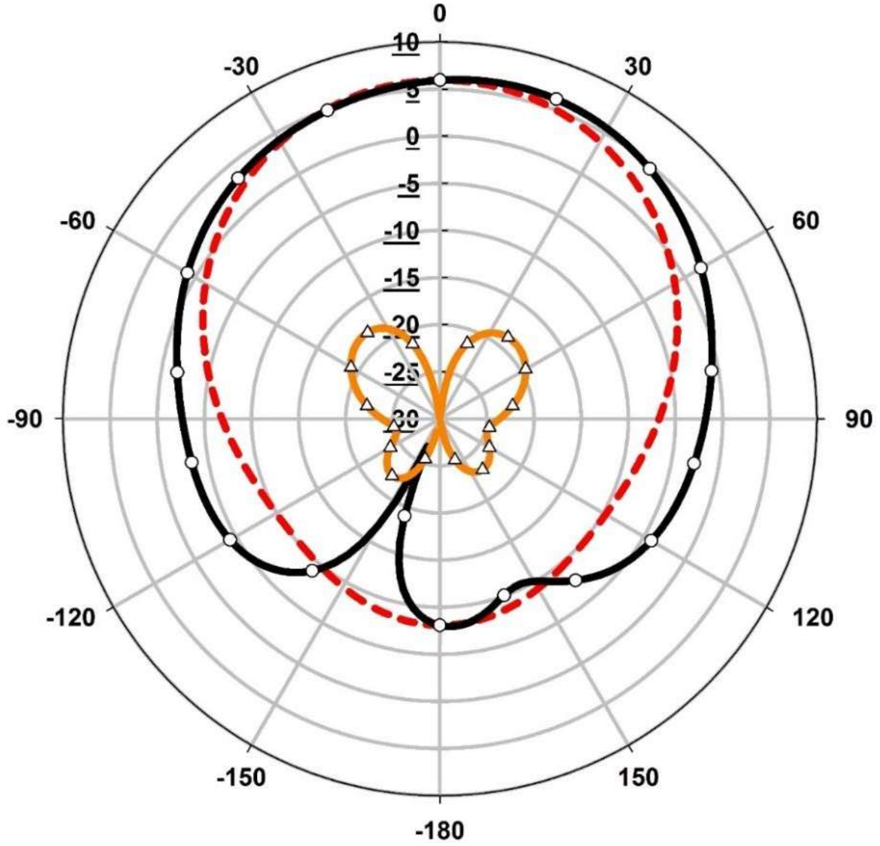
- Plot shows the comparison of measured radiation pattern with simulated pattern.
- Measured pattern shows strong ripples due to high cable losses in addition to the reduced Gain and high cross-polarizations.

After Adding Wideband Low Noise Amplifier To Boost The Transmitted Signal

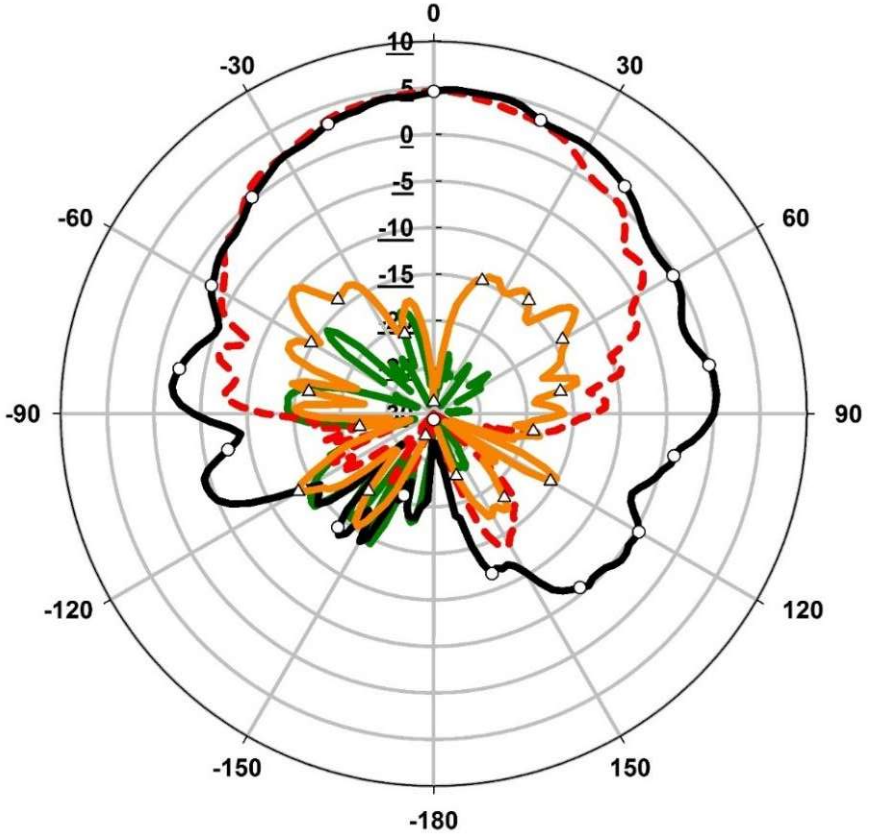


30 dB Wideband Power Amplifier

Realized Gain Radiation Patterns



Simulated Realized gain @14.6GHz
Peak Realized Gain=5.6 dBi

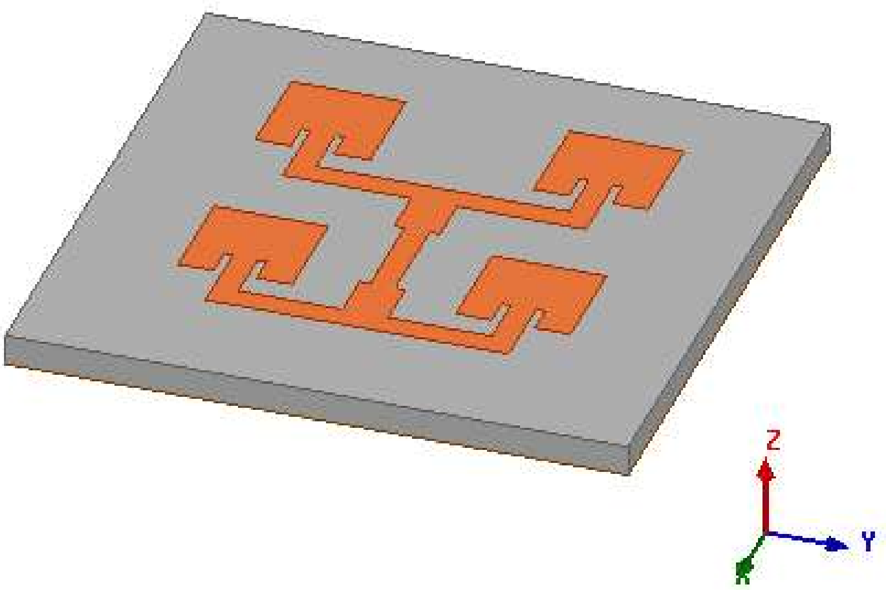


With amplifier
Peak Realized Gain=5.1 dBi

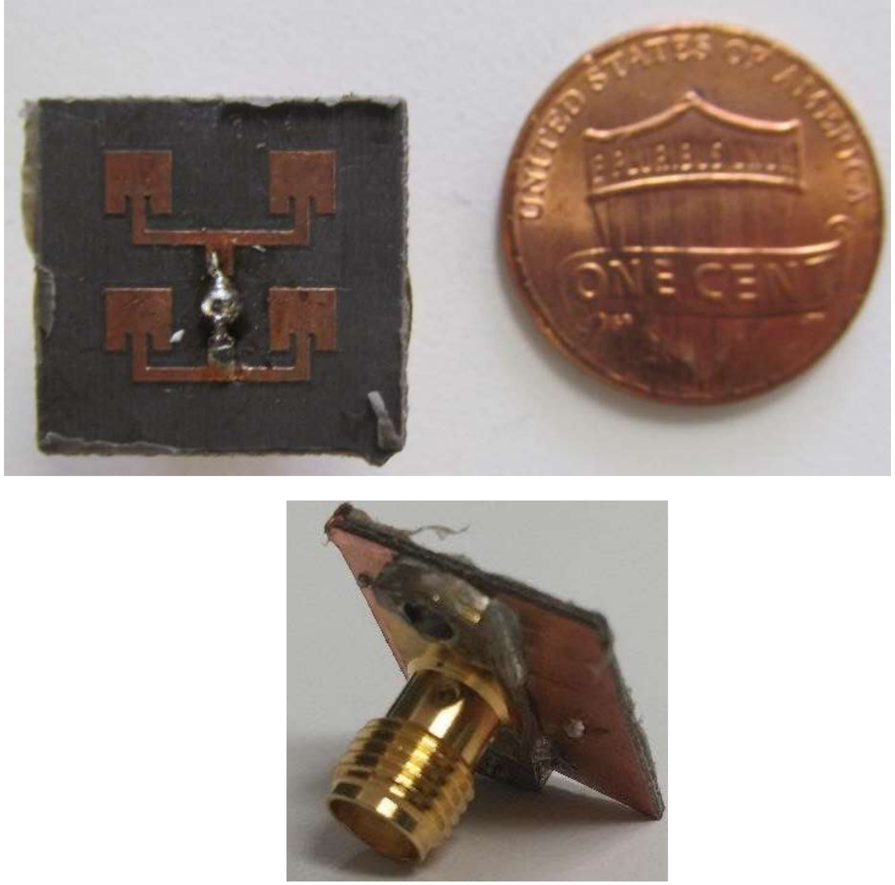
- The measured response shows higher cross polarization due to scattering from cables, AUT post, etc., in the anechoic chamber and imperfections in fabrication of antenna.
- The response is smoother compared to the case without using amplifier.

Pattern Measurement: Example 2

Corporate feed excited rectangular patch antenna 2x2 array designed around 30 GHz and milled using LPKF Protomat S-42 milling machine available in AML

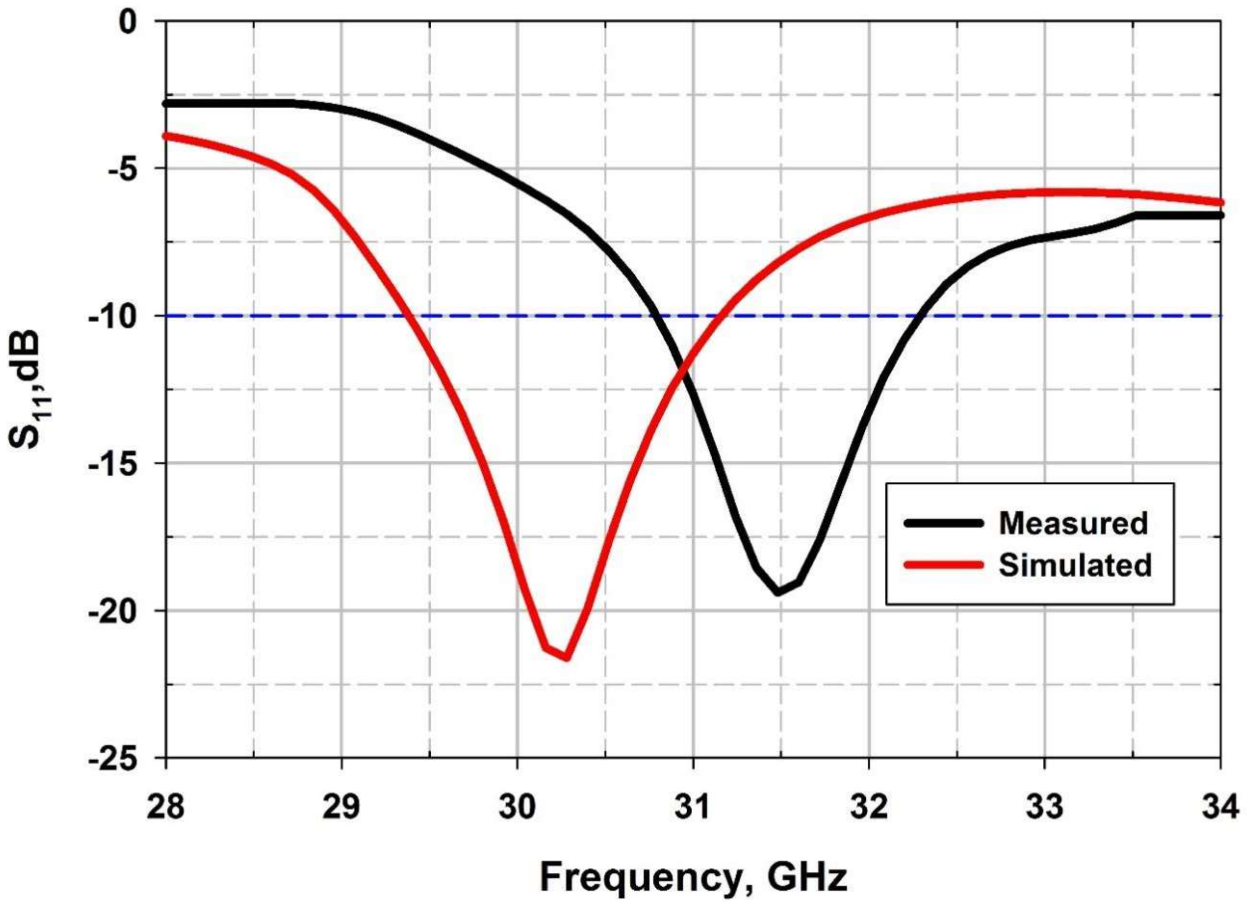


Simulated 2x2 Patch Array



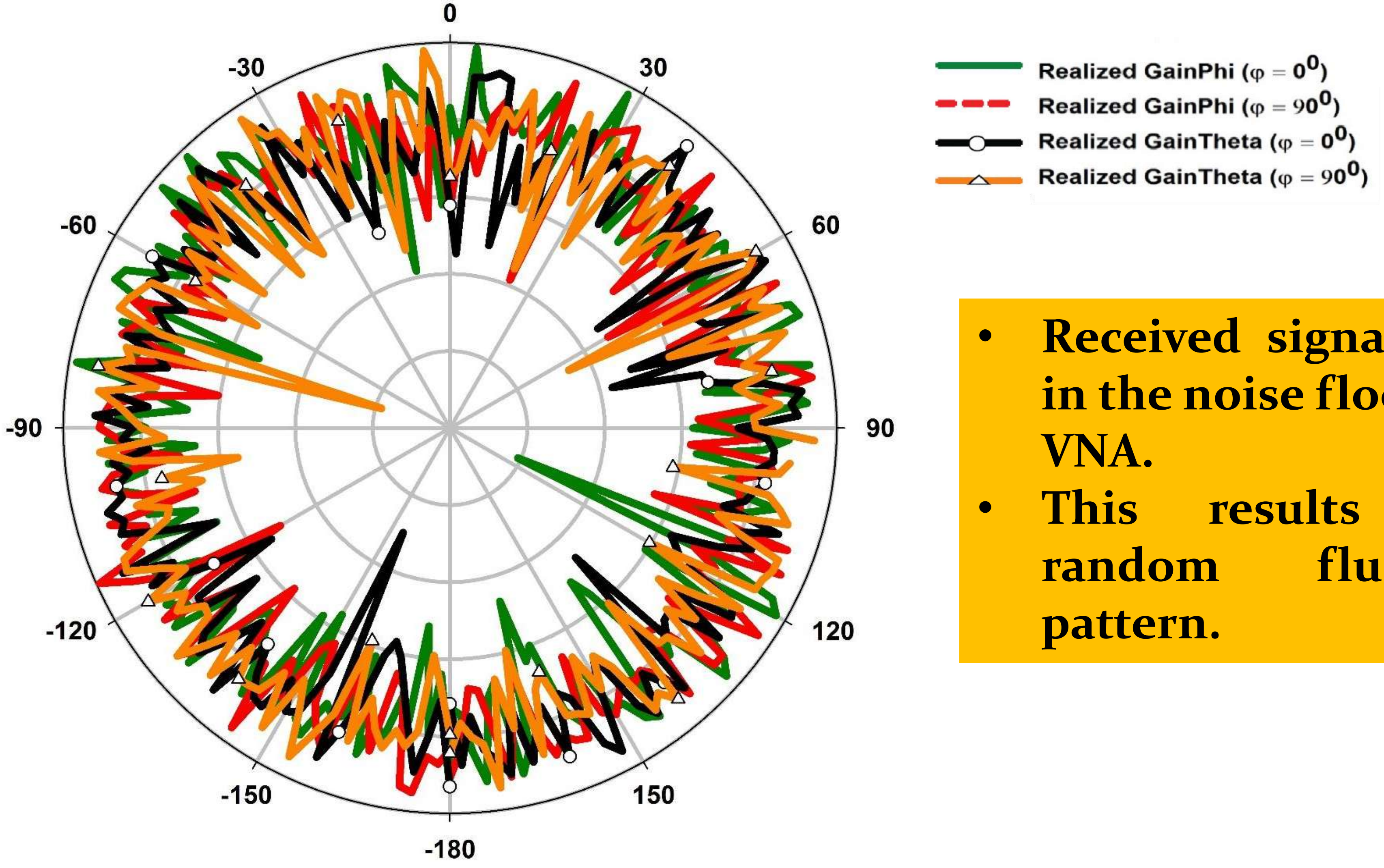
Fabricated 2x2 Patch Array

Reflection Coefficient Magnitude



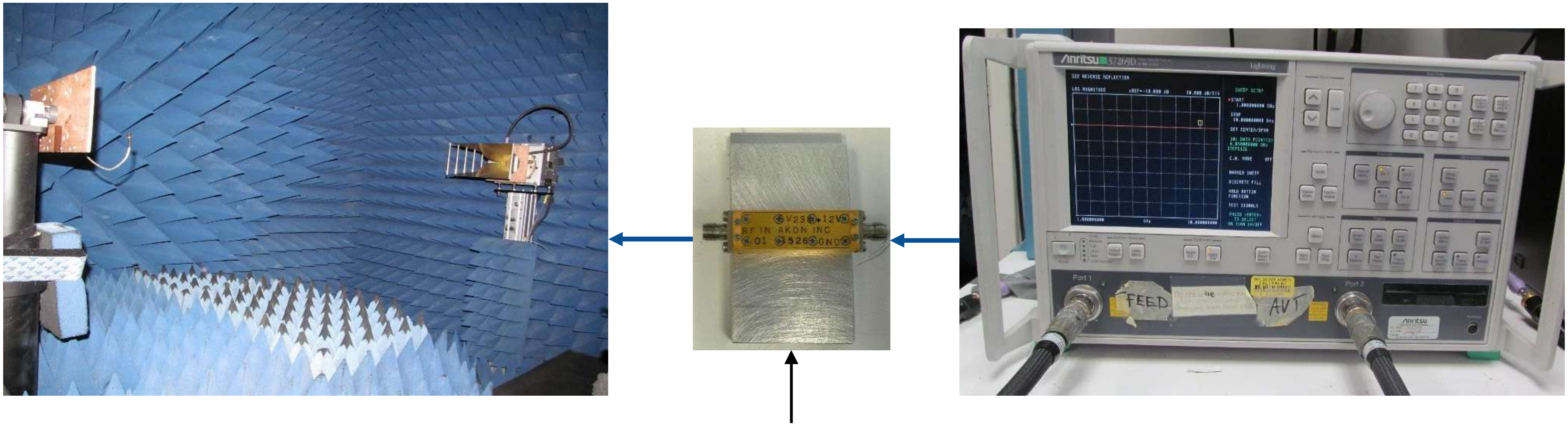
- Measured Reflection coefficient is shifted by 1 GHz towards higher frequency.
- This may be due to imperfection in fabrication and use of SMA connector instead of K- connector (Preferred).

Measured Pattern without using Amplifier



- **Received signal is lost in the noise floor of the VNA.**
- **This results in a random fluctuating pattern.**

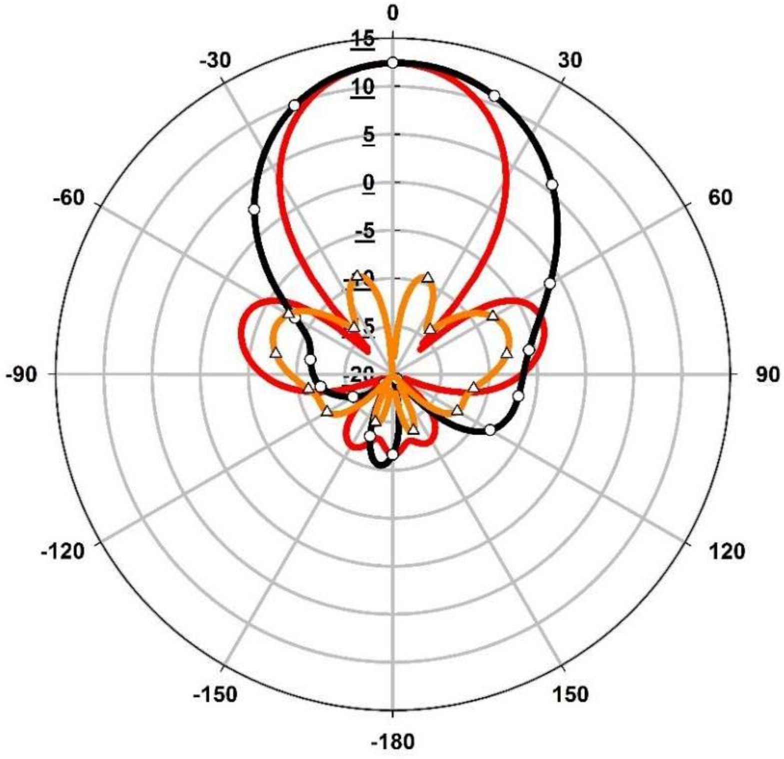
After Adding Wideband Low Noise Amplifier To Boost The Transmitted Signal



30 dB Wideband Power Amplifier

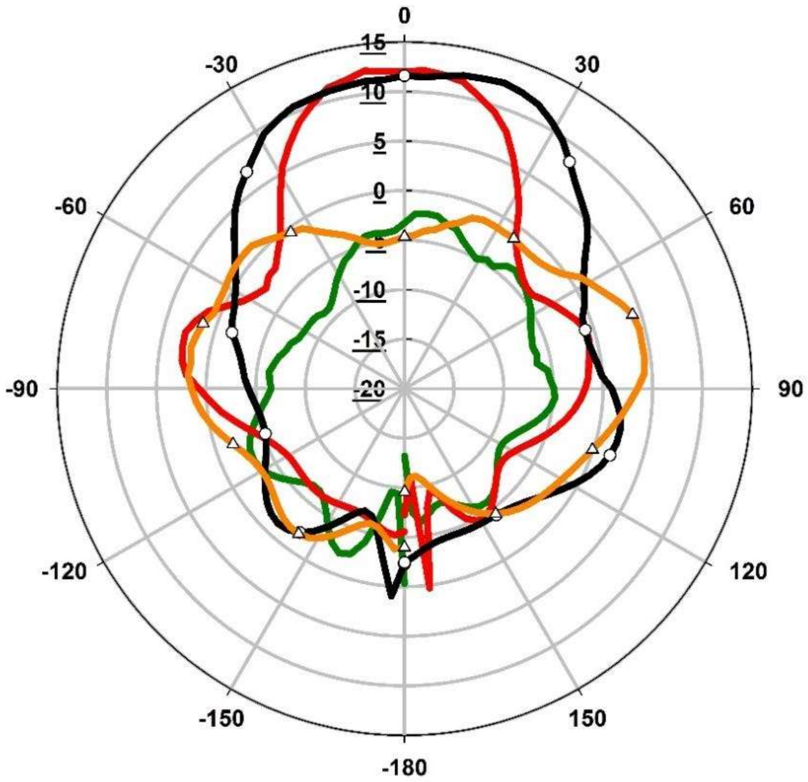
Realized Gain Radiation Patterns

Simulated pattern



Realized Gain ~ 12.2 dBi
@ frequency 31 GHz

Measured pattern

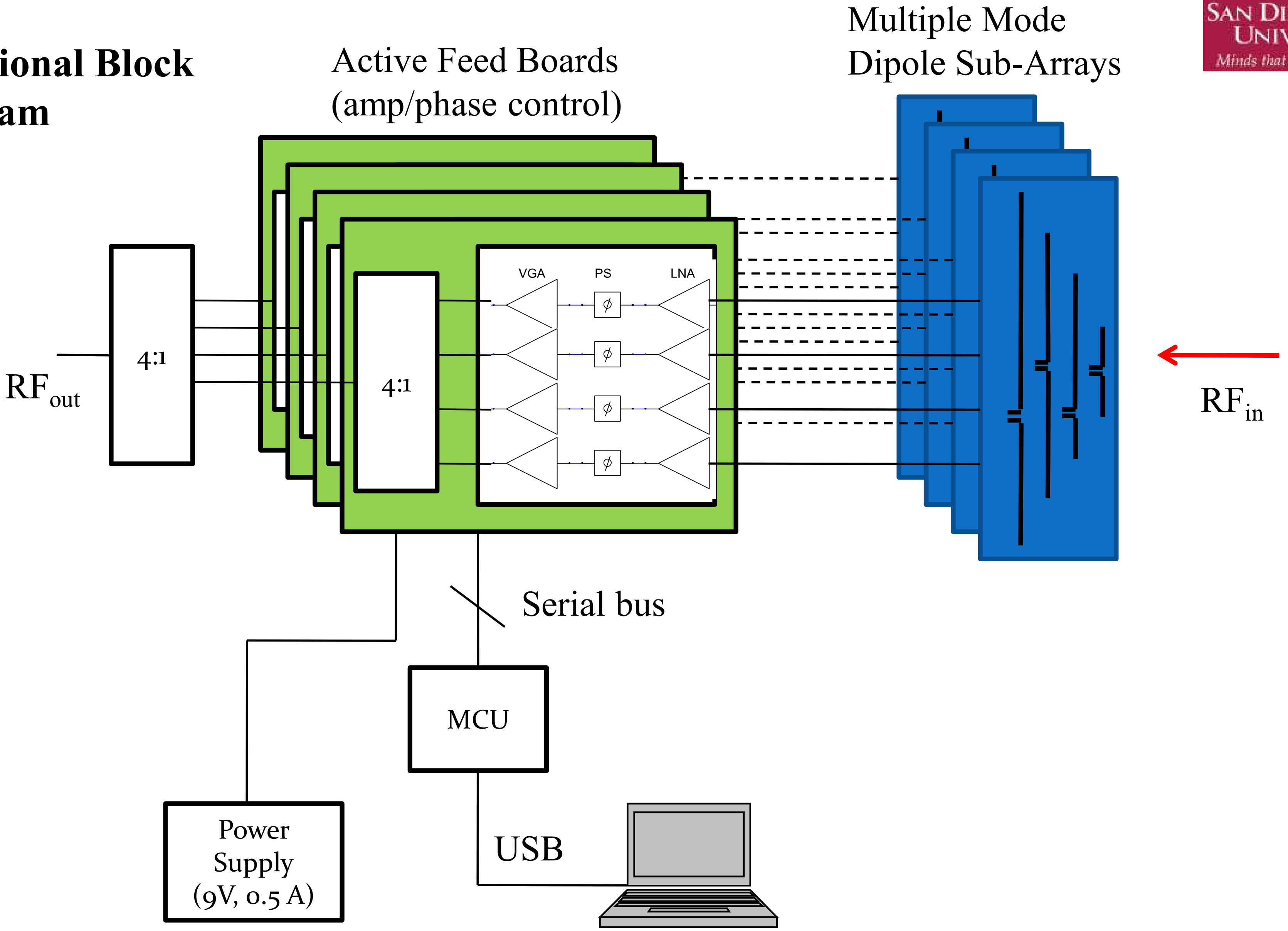


Realized Gain ~ 12 dBi
@ frequency 31 GHz

Measured patterns show higher cross polarization due to scattering from cables, AUT post, etc., in anechoic chamber and imperfection in fabrication of antenna.

Multiple Radiating Modes Based Beam Steering Antenna

Functional Block Diagram

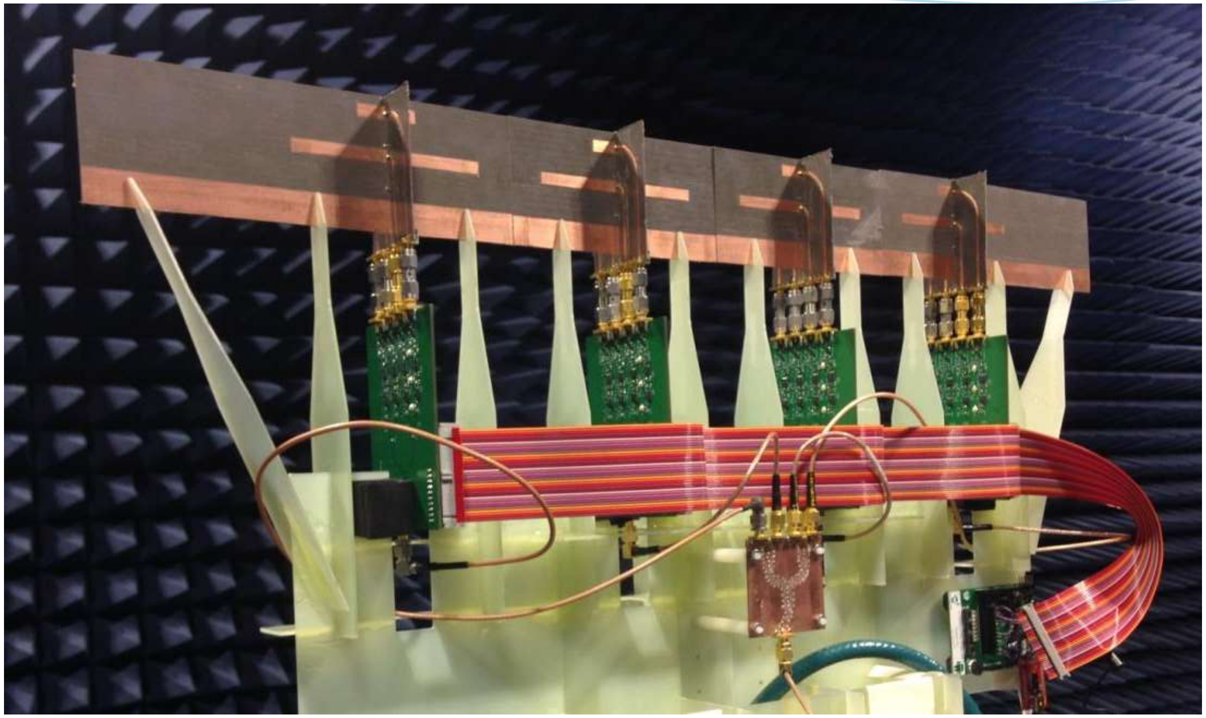


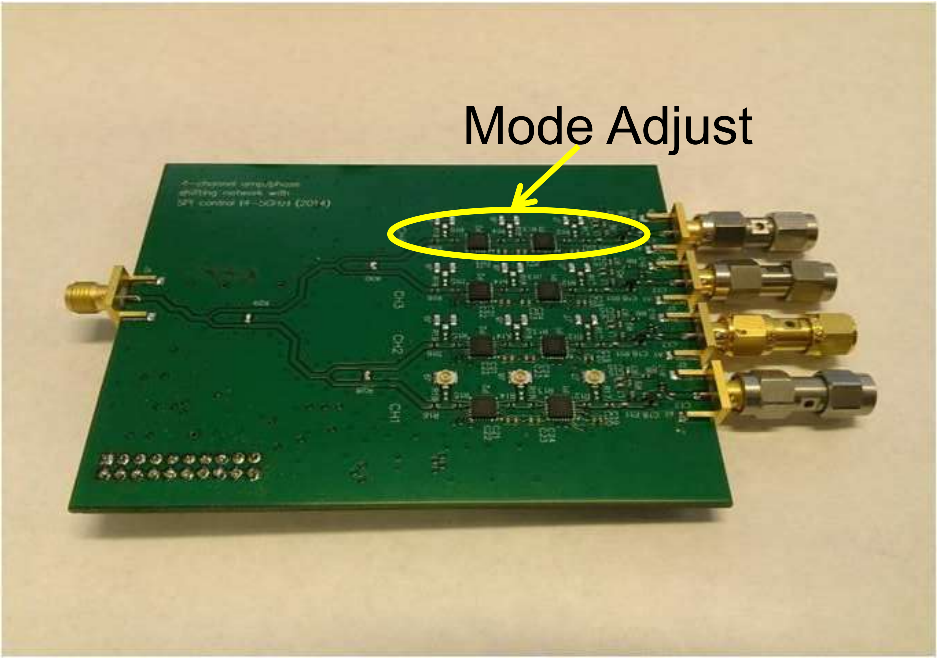
Active Feed Boards (amp/phase control)

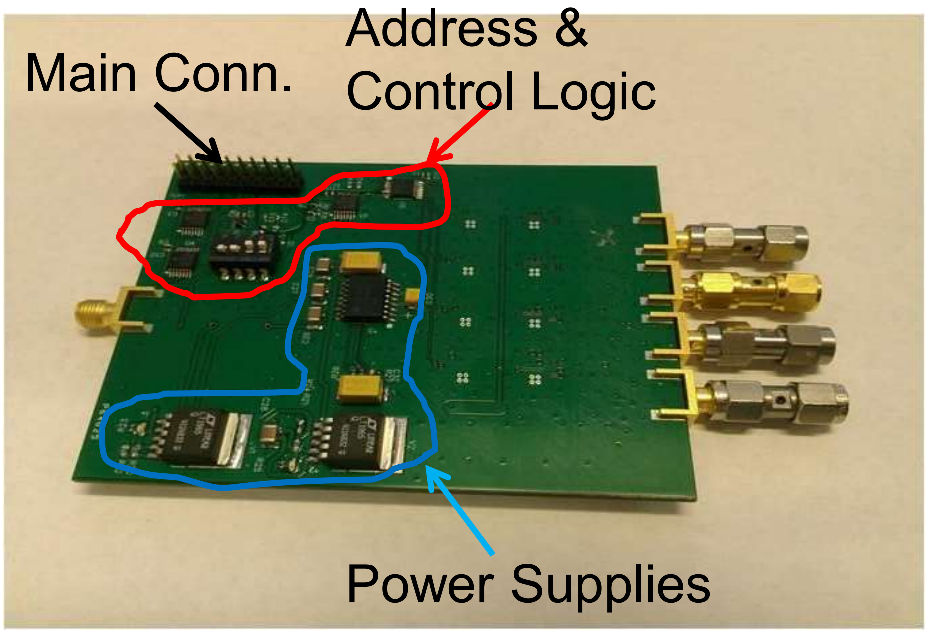
Multiple Mode Dipole Sub-Arrays

N. Labadie, **S. K. Sharma**, and G. Rebeiz, “A Novel Approach to Beamforming using Arrays Composed of Multiple Unique Radiating Modes”, ***IEEE Trans Antennas and Propagation, USA***, July 2015

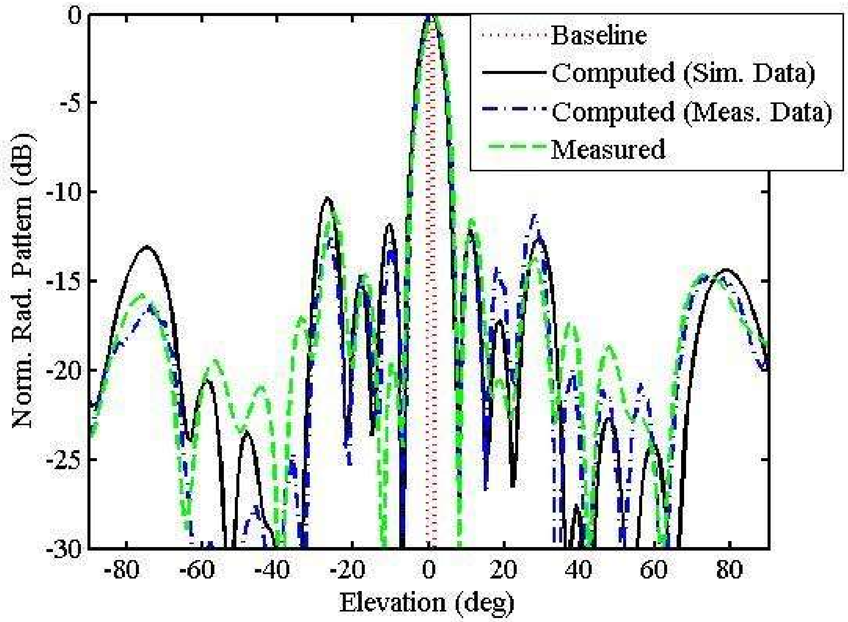
16-Element Active Dipole Array



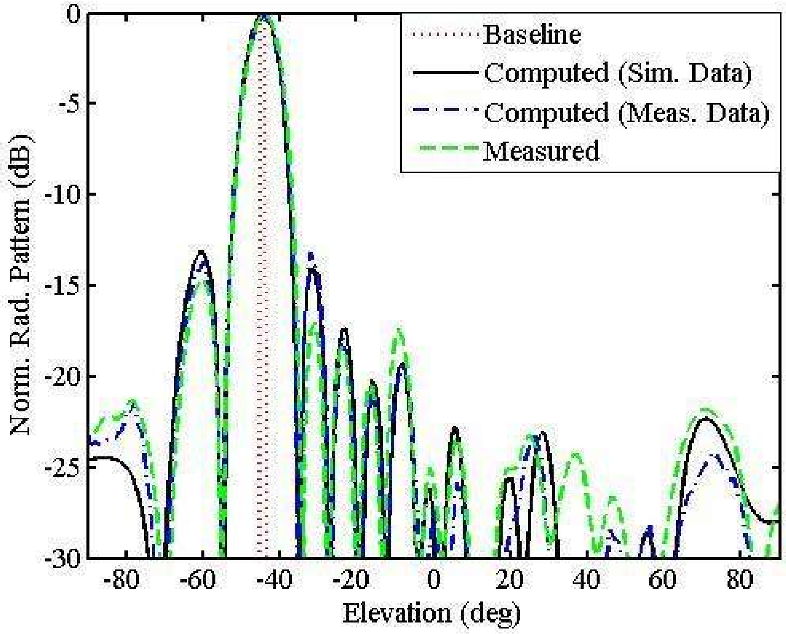


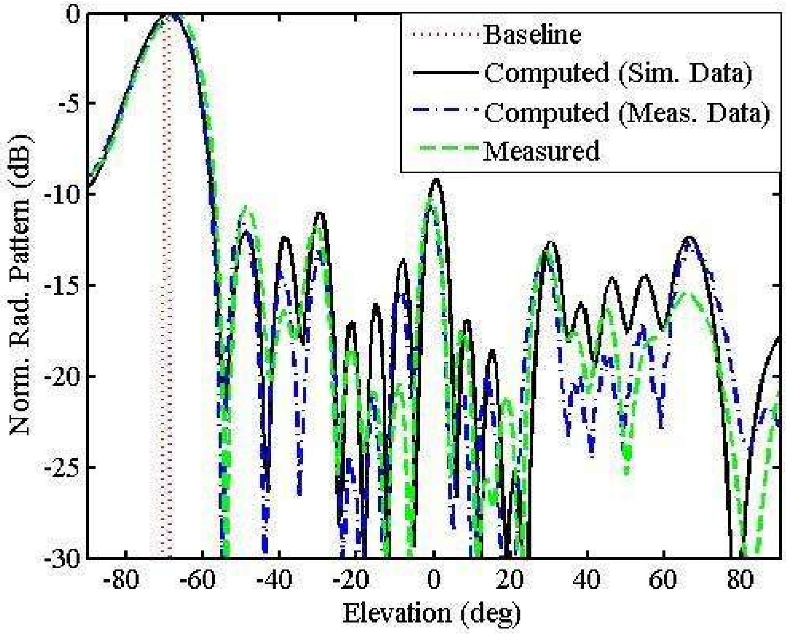


Scanned Radiation Patterns @ 4.6 GHz

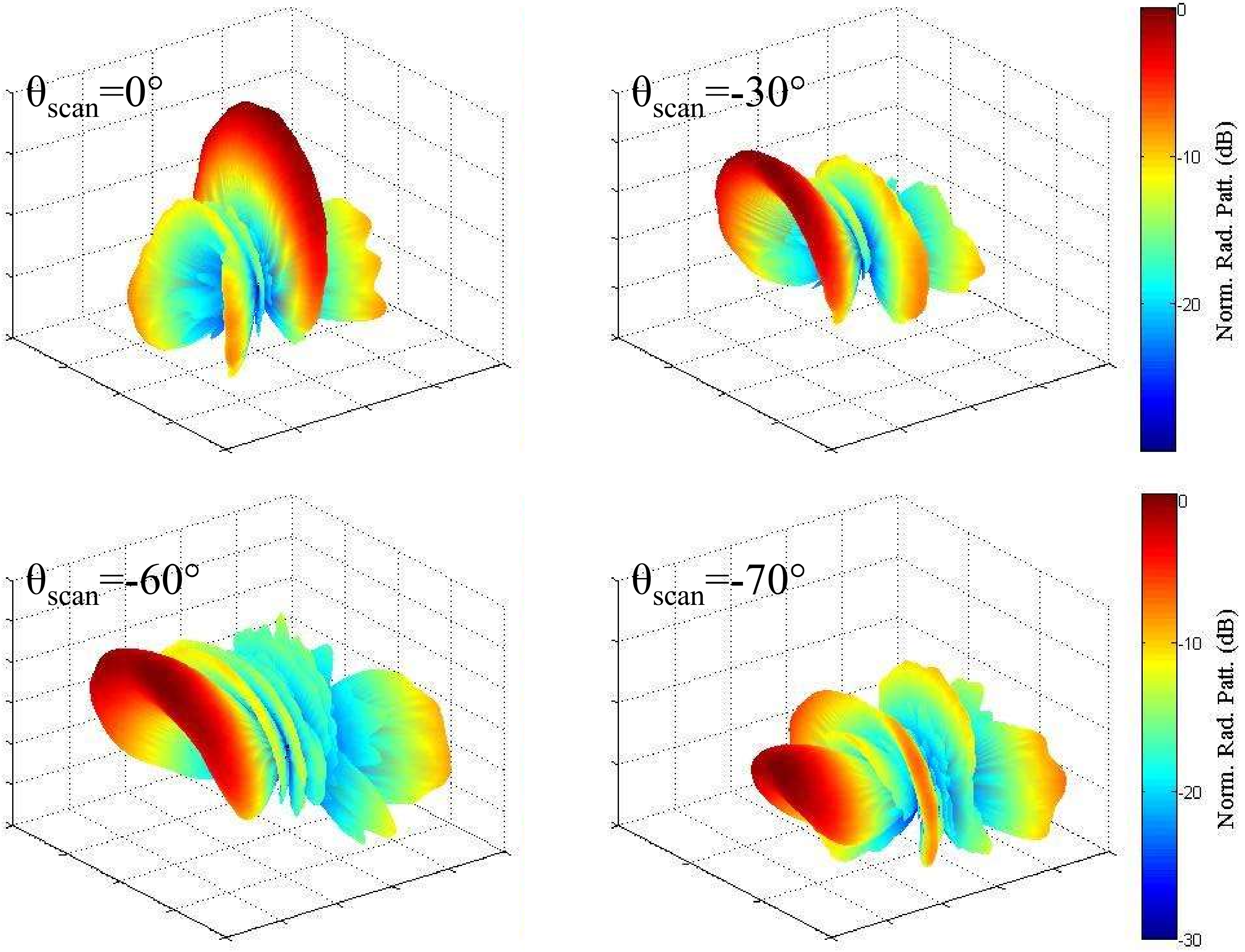


- Desired pattern is a simple pulse function to maximize directivity at desired scan angle.
- Small disagreements between computed and measured patterns are primarily due to
  - error in amp/phase shifter settings.
  - change in antenna loading from adjacent element settings.





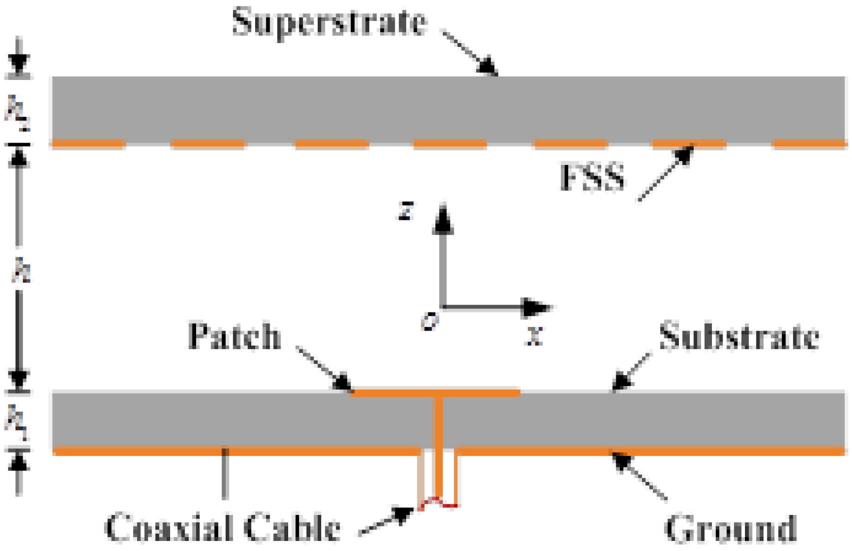
Measured 3D Radiation Patterns @ 4.6 GHz

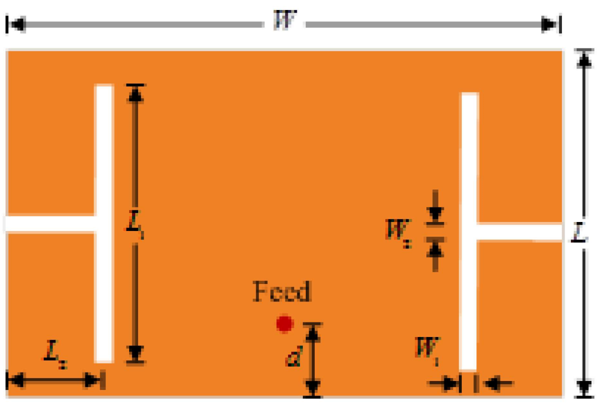


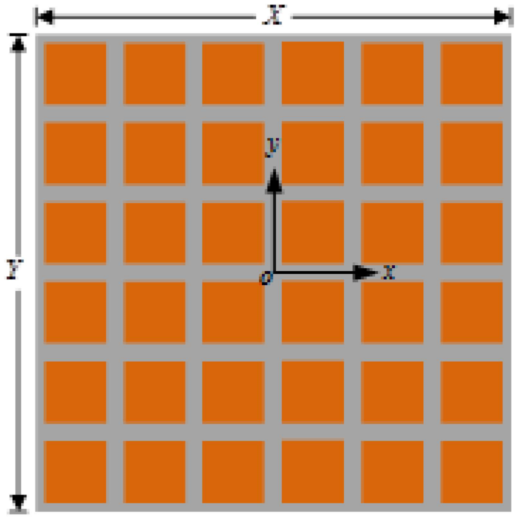
Beam scans to ±70 degrees with less than 3dB gain variation which is better than a conventional microstrip antenna based beam steering antenna.

A Dual Band High Gain Resonant Cavity Antenna with A Single Layer Superstrate

- A dual-band high gain Resonant Cavity Antenna (RCA) with single layer superstrate is proposed.
- Microstrip patch antenna with two T-shaped slots was used as feed system of RCA.
- T-shaped slots was used to modify the high order mode of original microstrip patch antenna to get directional pattern.







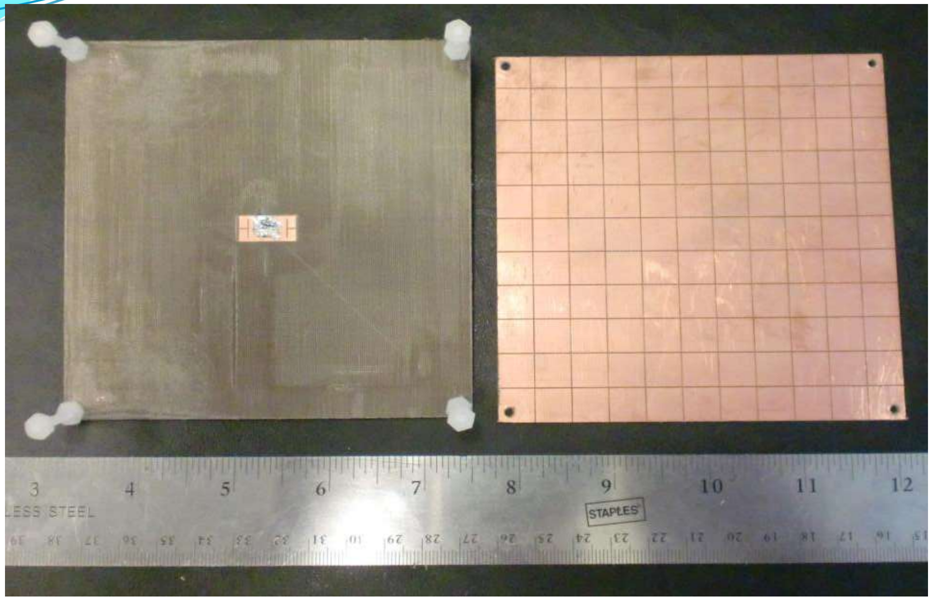
Substrate & superstrate (Arlon AD250A, thicknesses = 1.58mm, εr = 2.50 and tan δ = 0.0015)

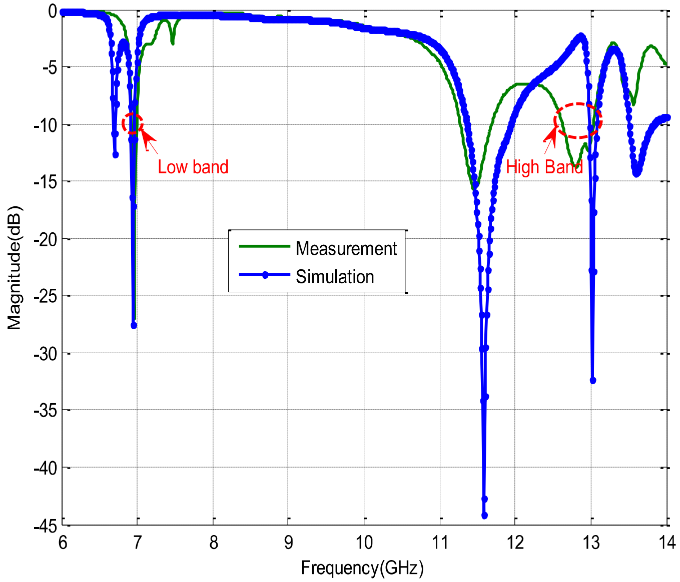
Design Parameters:

W = 15mm, L = 7.3mm, W_1 = 0.4mm, W_2 = 0.3mm, L_1 = 5.5mm, L_2 = 2.1mm, d = 1.95mm, X = 110mm, Y = 110mm.

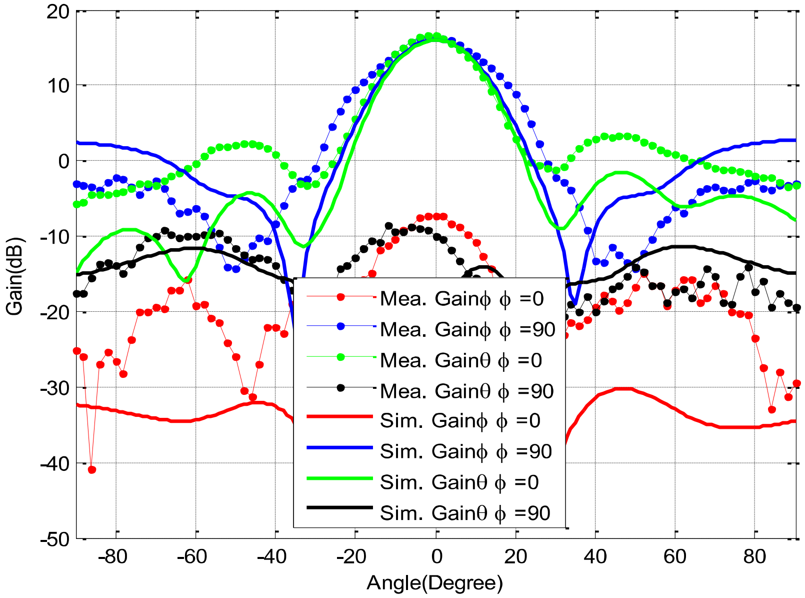
F. Meng and **S. K. Sharma**, "A Dual-Band High Gain Resonant Cavity Antenna with A Single Layer Superstrate", **IEEE Trans Antennas and Propagation**, May 2015

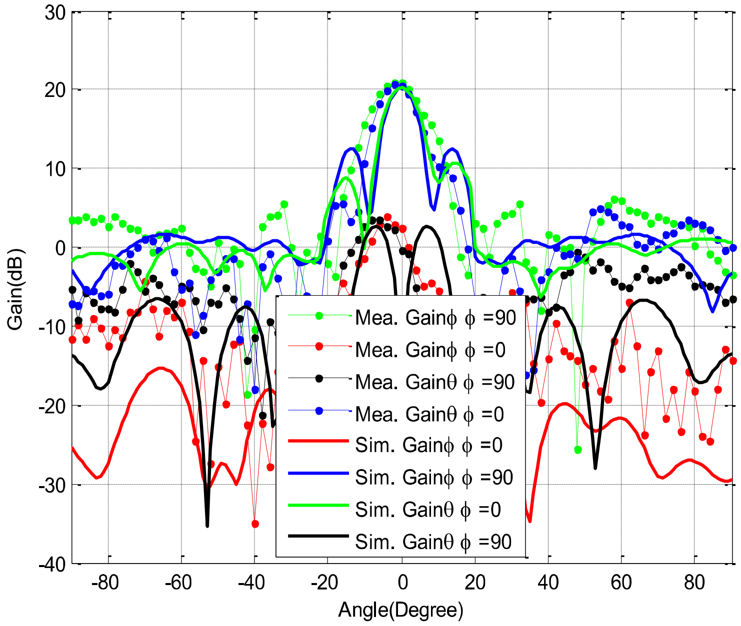
A Dual Band High Gain Resonant Cavity Antenna with A Single Layer Superstrate





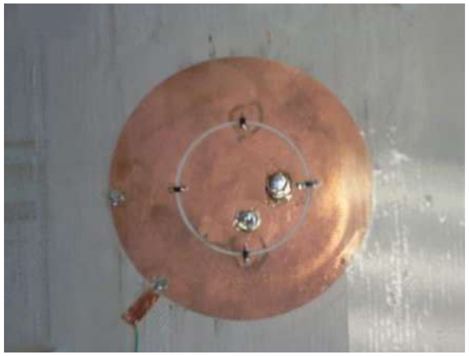
- **RCA yields around 16.5dBi and 20.9 dBi gain values at 7GHz and 13GHz, respectively.**
- **The RCA operated in dual-band with single polarization with frequency ratio of 1.93.**



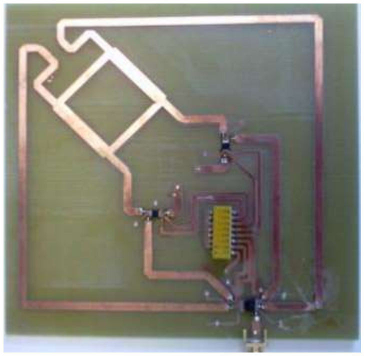


Frequency Tunable with Polarization Reconfigurable Antenna

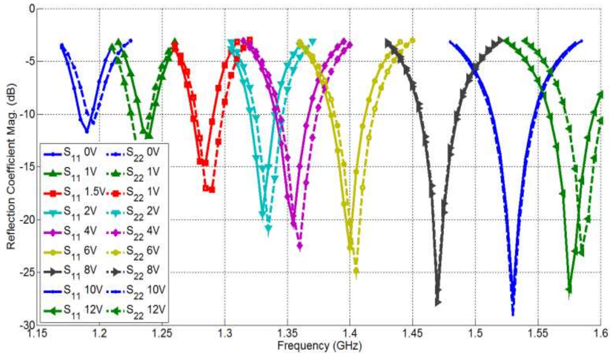
Frequency tunable with simultaneous polarization reconfigurable antenna was designed and developed for experimental verification.



(a)



(b)



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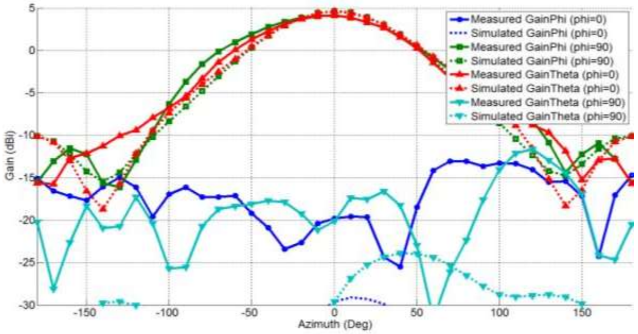

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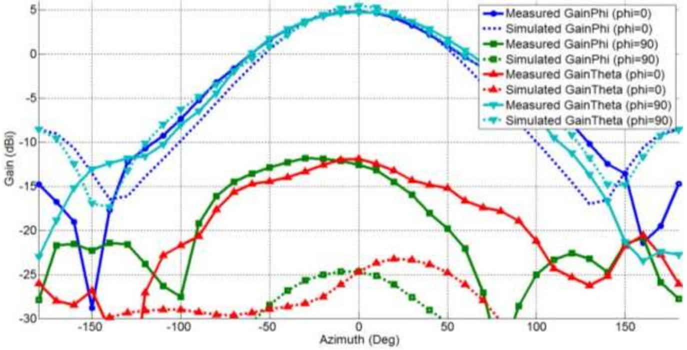

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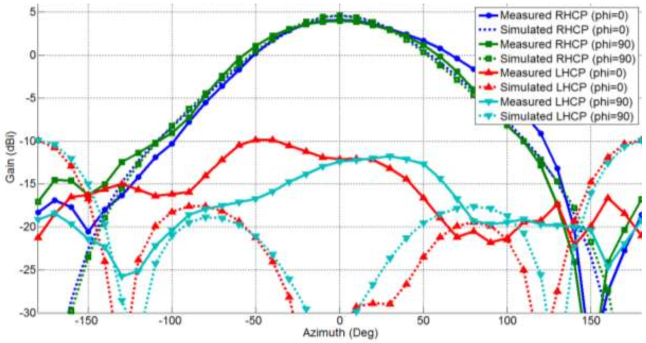

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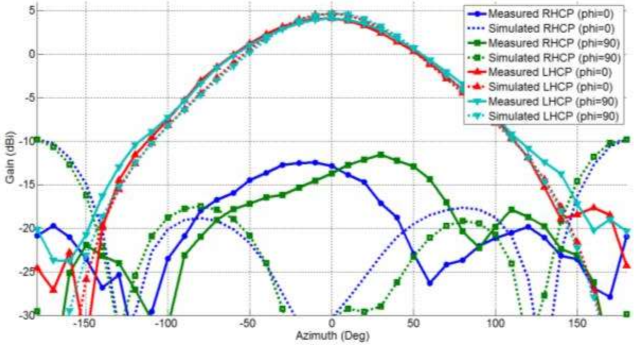

(g)

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Minds that move the world

B. Babakhani and **S. K. Sharma**, "Wideband Frequency Tunable Circular Microstrip Patch Antenna with Simultaneous Polarization Reconfiguration", **IEEE Antennas and Propagation Magazine**, USA, April, 2015.

Summary

- Gain and radiation pattern measurement and challenges at AML, San Diego State University presented
- Discussion limited to far-field pattern measurements
- Chamber and measurement set-up behavior different for higher frequency than the low frequency
- Adding high quality cables and power amplifiers are the means to improve received signal before processing for radiation pattern and gain results
- Examples of antenna measurement results discussed
- Some other antenna’s simulated and measured pattern results presented

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